Optimizing oxygen delivery in subsurface drip irrigation

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DOCTOR OF PHILOSOPHY

2010

A thesis submitted for the degree of Doctor of Philosophy

To

Centre for Plant & Water Science
Faculty of Sciences, Engineering and Health
CQUniversity Australia, Rockhampton

11 August 2010

ABSTRACT

Subsurface drip irrigation (SDI) is known as one of the most effective irrigation methods capable of improving water use efficiency through providing small amounts of water at short irrigation intervals and causing little or no water loss in terms of deep percolation, runoff and soil evaporation. However, temporal waterlogging within the root zone during and after irrigation events adversely affects root respiration, water and nutrient uptake and consequently plant growth. Therefore, irrigation of plants with hyper-aerated, or oxygenated, water could alleviate the impacts of waterlogging in the rhizosphere.

Recent studies reportedly showed that aeration of irrigation water by means of venturi air injector in SDI systems (known as oxygation) enhanced crop performance in hypoxic soils. However, there was evidence of non-uniform improvement in crop yield along lateral pipes which might be ascribed to non-uniform distribution of air flow along irrigation pipes. Moreover, under pipe inclinations ranging from 5º to 15º, preferential flow of air was reportedly observed in branching pipe systems (containing no emitters) for ratio of water to air flow in the range of 0.1 – 0.3.

In the current study, preliminary investigation on preferential flow of air into branching horizontal pipe layouts suggested that delivery of air bubbles from the first emitter on the lateral pipe closest to the junction of main pipe and manifold might have formed a zone of relative low pressure. It was speculated that the low pressure zone was responsible for occurrence of preferential air flow in the branching pipe systems.

Emitter cross sectional area (CSA), connector geometry and length, and pipe diameter caused a marked effect on the average as well as the spatial distribution of emitter air flow rates. A 1.5 times reduction in CSA caused a 2.5 times reduction in water flow rate, but only halved the air flow rate. The shape and protrusion distance of connectors into the pipe influenced various attributes of the air delivery to the emitters. The uniformity of the emitter air flow rate distribution for symmetric connectors expressed by Christiansen's uniformity coefficient (CUC) was found to be improved by 283% for a 46% increase in the pipe diameter. For asymmetric connectors, the corresponding enhancement in the CUC of the emitter air flow rates was 89% for the aforementioned increase in the pipe diameter. Addition of non-ionic surfactantto irrigation water improved the CUC up to 214% (for the dripperline), but reduced the magnitude of emitter air flow rates down to 83% (for the non-pressure compensated pot drippers). Furthermore, it was postulated that addition of surfactant enhanced the CUC values through an increase in the number of air bubbles in the irrigation pipe, whereas insertion of goof plugs immediately before the symmetric connectors improved availability of air bubbles to the remote emitters.

The response of grain sorghum, capsicum, spring onion, pak choi, beetroot, bean, vegetable soybean, and wheat to aerated irrigation water was explored. Non-uniform delivery of air flow along the irrigation pipe generally resulted in non-significant enhancement in the performance of the foregoing species. However, the aerated plants located in the first block in all the experiments (i.e. closest to the air supply) consistently showed marked growth and yield.

The findings of this study suggest that small size venturis might be used at the beginning of laterals instead of big ones on the main pipe, so avoiding the risk of preferential flow of air in branching pipe systems. The size of a venturi depends mainly on the magnitude of motive flow rate and the desired rate of air flow. Use of microdrip emitters (water flow rate < 0.5 L h^{-1}) instead of conventional ones (water flow rate 2.0 to 8.0 L h^{-1}) is expected to lengthen the oxygation time through marked reduction in water flow rate without causing considerable reduction in the emitter air flow rate. Thus, a larger amount of air will be supplied to the plant roots.

ACKNOWLEDGEMENTS

This thesis arose in part out of years of research done since I came to CQUniversity Australia. In that time, I have worked with a great number of people whose contribution deserve special mention. It is a pleasure to convey my gratitude to them all in my humble acknowledgment.

In the first place, I would like to thank my PhD supervisor, Professor David Midmore for his enormous supervision, advice, and guidance from the very early stage of this research as well as giving me extraordinary experiences throughout the work.

I gratefully acknowledge my co-supervisors, Professor Kerry Walsh and Doctor Surya Bhattarai for their advice, supervision, and crucial contributions.

I am indebted to Laurence Tait for his advice on the uniformity trials. I am especially grateful to Brock McDonald and Graham Fox for their support at various stages of my research.

I would like to gratefully acknowledge Linda Ahern for offering incredible support when required.

Words fail me to express my appreciation to my wife Sousan whose dedication, love, and persistent confidence in me, has taken the load off my shoulder.

My special thanks go to my sons Hossein and Sina who were always supportive to me towards the successful completion of this study.

DECLARATION

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ABBREVIATIONS

AE	Aeration efficiency
CUC	Christiansen’s uniformity coefficient
CEFAW	Concurrent equation of flow of air and water
CSA	Cross sectional area
C_f	Final concentration
C_i	Initial concentration
CRBD	Completely randomized block design
CRD	Completely randomized design
CEC	Cation exchange capacity
CWSI	Crop water stress index
DAS	Days after sowing
EGM	Environmental gas monitoring
EC	Electrical conductivity
ETc	Crop evapotranspiration
GenStat	General statistical package
ID	Internal diameter
IR	Injection rate
IRGA	Infra red gas analyzer
IWUE	Irrigation water use efficiency
LI	Light interception
LSD	Least significant difference
PRD	Partial root drying
PAR	Photosynthetically active radiation

RGD	Relative gas diffusivity
SLC	Submerged length of connector
SDI	Subsurface drip irrigation
SPAD	Soil-plant analyses development unit of Minolta camera
WUE	Water use efficiency
WUE_i	Instantaneous water use efficiency

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Chapter 1: General Introduction

Over 40 percent (by value) of agricultural products are obtained from irrigated lands, which constitute 18 percent of total arable lands in the world. From 1950 to 2007, there has been an almost twofold increase in the area of irrigated lands indicating paramount importance of irrigated agriculture concerning food security and growth in agricultural productivity (Molden 2007).

As the world population increases, less fresh water resources will be available for domestic, industrial and agricultural use. The largest amount of water is reportedly consumed by the agricultural sector, leading to increasing competition for water by domestic and industrial sectors. Population growth and scarcity of water for agricultural production has put food security for future generations at risk. The agricultural sector is forced to consume less water and produce more food, and it must do this by increasing crop water productivity (Zwart & Bastiaanssen 2004). Hence, the agricultural sector will be obliged to use irrigation water with more care. The use of more efficient methods of irrigation along with appropriate irrigation management has proven to be an effective way to save on irrigation water and/or to increase water productivity.

One of the most effective methods to supply water to crops, with little soil erosion, water deterioration, salt accumulation, runoff, and deep percolation, is drip irrigation (Brouwer et al. 1988; Fischenich 1999). The ability of drip irrigation in providing small amounts of water at short irrigation intervals, which results in sustaining relatively high soil moisture and available nutrients in the rhizosphere, is the main advantage of this type of irrigation over other pressurized or gravity irrigation methods (Carter & Howell 2000). The application of the surface or subsurface drip irrigation method reportedly reduces irrigation water loss including soil evaporation, surface runoff, and deep percolation of chemical pollutants, resulting in improved water and nutrient uptake by plants and enhanced water use efficiency (Ben-Gal & Lazarovitch 2003).

During an irrigation event, regardless of the method of irrigation, expulsion of soil air by the infiltrating waterfront will create at least temporary anaerobic conditions in the irrigated zone (Heuberger et al. 2001; Rawyler et al. 2002; Blokhina et al. 2003; Su & Midmore 2005). Low oxygen supply to roots restricts respiration, reduces production of adenosine triphosphate (Drew 1983, 1990) and energy-dependent nutrient uptake (Gibbs et al. 1998), and subsequent transport of nutrients to the shoot (Drew 1988). Experimental investigations (Loehwing 1934; Durell 1941; Went 1943; Grable 1966; Herr & Jarrel 1980), and modeling (Armstrong 1979; De Willigen & Van Noordwijk 1989; Biernbaum 1992) indicate that aeration of the rhizosphere enhances plant performance in solution culture as well as in the soil. Nonetheless, direct injection of compressed air into the soil for field crops is not practically feasible because the forced injected air escapes from the soil through the chimney effect from the point of injection. However, it has been shown that subsurface drip irrigation (SDI) is capable of concurrent supply of oxygen and water to the plant root zone up to 50 m from the venturi via air injector venturi, without loss of gas from the soil profile via ‘chimneys’ (Goorahoo et al. 2002). Recent studies have reportedly mentioned that aeration of the rhizosphere of crops irrigated by a SDI system increased growth and yield (Bhattarai et al. 2004, 2005, 2008; Goorahoo et al. 2007a, 2007b; Essah et al. 2009; Pendergast & Midmore 2006). Quite clearly, not only the quantity of air bubbles but also the uniformity with which they are delivered to the root zone through the emitters is a crucial issue. However, almost nothing is known about the distribution of air bubbles and the factors influencing the availability of air bubbles to emitters along a lateral pipe in a drip irrigation system, nor about responses to aeration between species with differing root morphologies, between soil types and between different methods to aerate irrigation water.

The specific objectives of the study were:

- To elucidate the distribution of emitter air flow rates along a lateral pipe in relation to a variety of factors, including pipe diameter, connector geometry, and emitter cross sectional area.
- To develop methods which result in improved uniformity of emitter air flow rate distribution along a lateral pipe.
- To compare the efficiency of two commercially available air supply systems (Mazzei™ vs. Seair™) in terms of enhancement in the performance of wheat grown on two soil types.
- To evaluate the influence of root morphology on plant growth response to aerated drip-irrigation water, through a study involving vegetable species of different rooting systems.
- To evaluate the impact of the addition of surfactant to the drip irrigation water supply, in terms of bubble size and soybean growth on two soil types.

1.1 Null hypotheses (H0)

(H0) 1: The availability of air bubbles to emitters along a lateral pipe is independent of pipe diameter, connector geometry, and emitter cross sectional area.

(H0) 2: Increasing turbulence at the vicinity of a connector or decreasing the water surface tension has no influence on the availability of air bubbles to the emitters along a lateral pipe.

(H0) 3: For a given supply of air flow from the air injector venturi, pak choi, bean, spring onion, and beetroot show similar responses to root zone aeration.

(H0) 4: Overall performance of subsurface oxygenated wheat via a venturi air injector or the Seair diffusion system will not differ significantly.

(H0) 5: Addition of surfactant to the aerated irrigation water will not significantly affect the overall performance of soybean.

1.2 Limitations of pot based studies

i. Unlike the field situation, the lateral diffusion of oxygen is limited by the sides of a pot;

ii. In contrast to the field situation, there is little interaction between soil and aeration treatments and other climatic and environmental parameters, most particularly rainfall, in the controlled environment of the screen house or glasshouse.

1.3 Overview of the thesis

The following chapter (Chapter 2) presents a comprehensive literature review of the research conducted on the aeration of the root zone of plants grown in soil or solution culture. In addition to aeration by means of air injector venturi, other sources of oxygen supply such as ozone or hydrogen peroxide are discussed.

Chapter 3 deals with the distribution of emitter air flow rates along lateral pipes and examines the effect of a number of variables including pipe diameter, geometry of connectors, and emitter cross sectional area on the uniformity of the distribution of emitter air flow rates and its impact on the emitter water flow rates. Then, the effect of different concentrations of a non-ionic surfactant on the enhancement of the uniformity of air flow rates is explored. Furthermore, the uniformity of air or water flow rates with or without surfactant and in the presence or absence of goof plugs (asymmetric connectors adapted to create local turbulence in the flow with their outlet-ends sealed, see Figure 3.6) were analysed for drip irrigation systems with pressure compensated or non-pressure compensated pot drippers connected to short or long symmetric or asymmetric connectors. Also, the uniformity of emitter air flow rates was tested for a non-pressure compensated integral dripperline. Finally, a brief trial was conducted to investigate the preferential flow of air bubbles for a number of piping layouts.

The effect of three aeration rates on the yield and physiological response of grain sorghum irrigated with a branching pipe system is discussed in Chapter 4. In Chapter 5, the influence of two emitter depths, two emitter cross sectional areas, and three aeration rates on the yield and growth parameters of capsicum is explored. It should be noted that the experiments mentioned in Chapters 4 and 5 were done before the trials described in Chapter 3. However, for the sake of completeness, these experiments (Chapters 4 and 5) are included in this thesis as the findings justify the need for further investigation into the factors affecting the uniformity of emitter air and water flow rates. Also, the time and effort spent on these ‘preliminary’ studies were critical for identifying additional gaps in oxygation research not currently reported in the literature.

The response of four vegetable species with different rooting systems consisting of pak choi, bean, spring onion, and beetroot to root zone aeration using a single lateral pipe for each treatment is presented in Chapter 6.

In Chapter 7, the results of two different techniques of irrigation water aeration (Mazzei™ air injector venturi vs. Seair™ diffusion system) on wheat grown on two soil types (Vertisol and Ferrosol) are compared. In Chapter 8, the effects of two rates of water aeration with or without surfactant on the performance of soybean grown on two soil types are analysed. Finally, the conclusions and recommendations that were made in Chapters 3-8 are summarized and consolidated in Chapter 9.

Chapter 2: Literature Review

In regions where the amount of rainfall is insufficient or distributed poorly throughout the growing season, irrigation is undertaken to meet plant water requirements. Nevertheless, application of even depth of water to all plants in a field is neither possible nor economically feasible. It follows that a non-uniform infiltrated depth of irrigation water is the main cause of reduction in crop yields. Drip irrigation systems are capable of offering the highest irrigation uniformity compared with other irrigation methods (Wu 1987; Bhatnagar & Srivastava 2003; Kirnak et al. 2004). Drip irrigation, also known as trickle irrigation, is the delivery of very small quantities of water from small diameter low density polyethylene pipes via outlets called drippers or emitters (Brouwer et al. 1988). Emitters are the core of the drip irrigation system and are made of plastic materials. The critical objectives in design and manufacturing of emitters are low flow rate (0.5-8 L h^{-1}), low vulnerability to clogging, low production cost, and high durability. Attaining low flow rate necessitates a high extent of pressure dissipation. The flow rate is determined by the pattern and dimensions of the emitter water cross sectional area as well as the water pressure at the inlet of the emitter. The smaller the cross sectional area, the lower the emitter discharge at a given pressure (Sne 2009). The relationship between the emitter operating pressure and flow rate is calculated with the following equation:

$$Q = K \times H^x$$

where: Q = emitter discharge, L h^{-1}

K = emitter constant, depends on the units of discharge and pressure head

H = pressure head at the inlet of the emitter, m

x = emitter discharge exponent

The emitter exponent indicates the specific relationships between the operating pressure and the discharge of the emitter. The range of emitter exponents is 0 - 1.0. Emitters with a laminar flow pattern have high exponents, in the range of 0.7 - 1.0. Emitters with a turbulent flow pattern have exponents between 0.4 and 0.6 (Sne 2005).

Emitters are generally classified as pressure compensating and non-pressure compensating. In pressure compensating emitters, pressure fluctuations above the threshold of the regulating pressure do not affect the discharge. The regulating pressure is the pressure range in which regulation of flow rate takes place. Compensating emitters have exponents which approach zero in the regulated flow range. The compensating mechanism narrows or widens the internal water passageway as the pressure changes, adjusting the friction head losses that keep the discharge constant. In contrast to the pressure compensated emitters, the non-pressure compensated emitters are sensitive to pressure variations at the inlet of the emitter. The larger the emitter exponent, the more sensitive is the flow rate to pressure variations (Sne 2005).

In SDI under certain circumstances, the functionality of emitters (particularly the non-pressure compensated ones) is adversely influenced by a phenomenon known as soil overpressure or backpressure. In a SDI system, flow of water from an emitter results in formation of a small cavity around the emitter, allowing free flow of water from the emitter into the soil. Saturation of soil pores with water leads to the development of positive pressure around the emitter because the soil hydraulic properties limit flow of water through the soil (Shani & Or 1995). Using non pressure-compensated emitters with SDI might lead to formation of back-pressure at the outlet of the emitter, and thereby reduction in water flow rates and low uniformity in water application (Warrick & Shani 1996). Use of pressure compensated emitters of low flow rate and high working pressure alleviates issues concerning non-uniformity and back-pressure for subsurface drip irrigation. Furthermore, it has been shown that growth of plants might not only lead to elimination of the back-pressure phenomenon but also in certain situations plant growth results in the development of a negative pressure head in soil (Clothier & Green 1994, 1997). When the emitter flow rate is sufficiently low, water uptake by plant roots exceeds water discharge from emitter, thus preventing the development of back-pressure. In subsurface drip irrigation, the formation of a positive pressure head in the saturated zone around emitters might lead to the development of a pressure gradient between the saturated zone (high pressure) and soil surface (low pressure zone), causing an upward flow of water towards the soil surface and even water ponding, thereby negating the objectives of SDI (Ben-Gal & Lazarovitch 2003).

Depending on the soil type and drainage characteristics, irrigation practices will have transient to long-term adverse effects on soil oxygen content (McLaren & Cameron 1996; Thongbai et al. 2001). The negative effect of irrigation on soil oxygen is more severe on heavy clay soils for a given soil water potential than on coarse textured soils. In fine textured soils irrigated with SDI, continuous discharge of water for a long duration might result in soil oxygen deprivation in part of the root zone which is close to the emitter (Bhattarai et al. 2005). It has been found that application of water via a point source subsurface drip irrigation system has a remarkable impact on plant root functioning and soil water gradient through the overall distribution pattern of soil oxygen. It was shown that the roots of crops irrigated by a drip system concentrated on the external boundary of the volume of the irrigated soil where the rates of oxygen diffusion were larger than those recorded in the middle of the volume of the irrigated soil (Silberbush, Gornat & Goldberg 1997). Nonetheless, there is experimental evidence indicating that roots of sweet corn (Bar-Yosef, Sagiv & Markovitz 1989) and cotton (Hutmacher et al. 1998) were concentrated adjacent to the emitters, because after redistribution of water within the soil profile, a sufficient amount of air and moisture will be available in that zone (i.e. the centre of the irrigated soil volume) for optimal root functioning.

Root respiration supports root metabolic activities which affect the aboveground crop performance (Meek et al. 1990). A sufficient amount of oxygen for root respiration depends on the oxygen diffusion processes in the root zone (Benjamin, Neilsen & Vigil 2003). Low concentrations of oxygen in the rhizosphere associated with irrigation (Hodgson & Chan 1982; Jayawardane & Meyer 1985), sodicity (Barrett-Lennard 2003), compaction (Agnew & Carrow 1985), and salinity (Bathke et al. 1992) in different types of soil have been identified as major constraints for achievement of yield potential. Quite evidently, investigations indicate that raising oxygen concentration of a waterlogged rhizosphere (less than 2 mg L^{-1} O_2) to normoxia (~ 6 mg L^{-1} O_2) significantly ameliorates plant performance (Gibbs & Greenway 2003; Rowe 2001). Efforts to oxygenate the crop root zone in hypoxic or anoxic environments go back 150 years. Sachs's observations in 1860 (cited in Durell 1941) indicated that aeration of the root zone through solution cultures could increase crop growth. In 1901, Arker (cited in Durell 1941) claimed that the growth of lupin roots, in both soil and water cultures, was accelerated by passing air through the root zone.

Durell (1941), in his comprehensive experiments on the effects of aeration of the nutrient solution and its relationship to the fruit production and vegetative growth of tomato, noticed that optimum root growth (dry weight) and fruit production (fresh weight) were obtained when the nutrient solution was supplied with 2.5 mL of air per minute per plant. Aeration rates > 2.5 mL per minute per plant had a non-significant effect on the production of fruit and root growth. However, the greatest stem and leaf production was obtained with a supply of 250 mL of air per plant per minute. These results indicate that for tomato, the air requirement for optimum root growth and fruit production is relatively low and amounts of air flow in excess of 2.5 mL per minute per plant have little effect. On the other hand, both stem and leaf growth of tomato showed a response to the highest rate of air supply indicating that the air requirements for optimum stem and leaf production are high. Boicourt and Allen (cited by Bhattarai et al. 2005) revealed that application of daily air flow for one hour through subsurface tiles and glass wool underlaid in soil beds resulted in a noticeable increase in linear growth of tea rose.

Loehwing (1934) studied the response of sunflower and soybean, cultivated in pots filled with 12 kg of sand or 10 kg of loam soil, to aeration of the root zone by means of a continuous stream of air approximating 100 litres per day. He showed that, generally, aerated treatments produced early rapid growth resulting in taller and heavier plants compared to the non-aerated controls. The root system in aeration treatments was more fibrous, and was associated with more rapid nutrient uptake resulting in larger ash content, phosphorus, potassium, and calcium per plant in terms of absolute weight of whole plants. Also, Loehwing mentioned that crops show a higher tolerance to over-aeration as temperature increases. This might be explained by the fact that an increase in soil temperature will be accompanied by an increase in respiration by the soil biota and a reduction in solubility of oxygen in the soil solution. Consequently, this will result in a higher demand for oxygen consumption. This in turn, would alleviate the negative impacts of over-aeration to some extent, provided that the soil moisture is high enough to prevent drying of the roots. Moreover, the root injury and the subsequent growth retardance of species cultivated in soil cultures were largely attributed to the evaporative effect of dry air on the root system.

Extensive experiments were conducted by Vlamis and Davis (1944) on several plant species of differing levels of root sensitivity to oxygen requirements, both in soil and solution culture. In their soil culture experiments, they compared the growth of tomato, rice, and barley in loam or clay soil under identical conditions of submergence and drainage for six weeks. Contrary to barley and tomato, rice showed enhanced growth, especially concerning the root system, under the anaerobic conditions. The potassium content of the sap in the drained roots of rice averaged twice that of the submerged roots. This difference may be largely due to the dilution effect of the excess water on the concentration of salt in the flooded soil. In their solution culture (Hoagland’s solution) experiment, tomato, rice, and barley were grown in 1.89 L containers for six weeks. In addition to the non-aerated control, different gases including air, carbon dioxide, and nitrogen were supplied under pressure, separately. Aeration of the submerged roots was achieved at the rate of three litres per hour per container. The results were consistent with most of the observations from the soil experiment. Aeration increased tomato root and shoot fresh weight nearly to the same degree by over 100% compared to the non-aerated treatment. As for barley, the aerated treatment in comparison with the control showed a 2.5% and a 24% increase in root and shoot growth, respectively. The aeration effect on fresh weight of rice was negligible.

Exposing the roots to nitrogen gas reduced tomato roots and shoots by about 90%. Barley shoot and root fresh weights were 45 and 30% smaller in the nitrogen treatment than the control, respectively. There were no significant differences in the fresh weights of roots and shoots of rice between the nitrogen and control treatments. In contrast to the effect of nitrogen, carbon dioxide was lethal to all species.

Erickson (1946) found that tomato plants in his non-aerated solution treatment showed an increasing limitation in both growth and water consumption compared to the aerated treatments. No difference in root growth was observed when the root zone was aerated with pressurized gas mixtures containing 8.0, 14.4, 21.6, 28.0, and 36.8 mg L^{-1} of dissolved oxygen, except at the highest value where the growth was significantly retarded.

In the past decade, ozone has been employed as a source of oxygen for roots. The ozone molecule is very unstable and will readily break down into its original form as $2O_3 \rightarrow 3O_2$. Sloan and Engelke (2005) studied the growth of creeping bentgrass in a sand medium irrigated by ozonated water. The treatments consisted of samples irrigated from above with tap water containing 6-8 mg L^{-1} dissolved oxygen (control), aerated water (12 mg L^{-1} dissolved oxygen), and ozonated water with ozone concentration of 0.7-0.9 mg L^{-1}. Relative chlorophyll contents of bentgrass measured 40 days after imposition of water treatments in samples irrigated with ozonated and aerated water were 228 and 222, respectively, which were significantly higher than that in the control (189). At 90 days after imposition of water treatments, the relative chlorophyll content for the control, aerated, and ozonated treatments were 156, 147, and 183, respectively. The superiority of the ozone treatment over the control (and to some extent, over the aeration treatment) in enhanced plant growth, was attributed to the mineralization of organic residues and consequent release of nutrients in the surface layer and crown of the bentgrass cores. Raub, Amrhein and Matsumoto (2001) reported that the electrolyte concentration in soil leachate, including ammonium and nitrate, were increased under ozonated water. It is probable that irrigation of bentgrass cores with aerated and ozonated water enhanced availability of nutrients to plant roots by increasing the solubility of the nutrients. Ozonated water significantly increased weights of bentgrass crown at 70 and 274 days after imposition of the water treatments. Nonetheless, root mass was not significantly affected by the water treatments at any of the sampling times or depths. According to findings by Raub, Amrhein and Matsumoto (2001), since ozone-related reactions are limited to about less than 2 mm from the soil surface, it is likely that the significant effect of the ozone treatment in the experiment conducted by Sloan and Engelke (2005) was restricted to the crown area of the bentgrass cores. It should be noted that the concentration of ozone used by Raub, Amrhein and Matsumoto (2001) was over 12 times higher than that used by Sloan and Engelke (2005).

In addition to aeration and ozonation, other sources of oxygen supply, such as hydrogen peroxide, have also been examined. Decomposition of one molecule of H_2O_2 will result in one molecule of water plus half a molecule of oxygen. Walter, Heuberger and Schnitzler (2004) conducted two pot experiments, one in soil culture to screen susceptibility to oxygen deficiency, and one in nutrient solution, to study the effects of compressed air and hydrogen peroxide on the root and shoot growth of tomato, cucumber, bean and zucchini. In the soil culture trial, treatments comprised flooding the pots with deionized water for three days; thereafter the pots were drained for three days for the plants to recover. In the control treatment, soil water content was maintained at field capacity for the optimum growth of the plants. The results indicated that zucchini was the most tolerant to oxygen deficiency of the four species and did not exhibit signs of wilting after the flooding period. In contrast to zucchini, cucumber was less tolerant to waterlogging in the rhizosphere. This species showed signs of wilting after two days of waterlogging. The growth of waterlogged beans and tomatoes was seriously slowed down compared to that of the control. It was concluded that bean was the most sensitive to oxygen deprivation as it showed signs of wilting after one day and never recovered after drainage. Formation of adventitious roots was observed for this species. Tomato was very intolerant to waterlogging stress compared to zucchini and cucumber, and only some of the flooded tomatoes regained full turgor after drainage. However, the adventitious roots of tomato showed the most vigorous growth. Due to the high level of inundation (3 cm above the soil), some tomato plants failed to recover from soil waterlogging, so that the plants could not generate adventitious roots. These researchers concluded that the ability of the species in inducing adventitious roots was the main reason for recovery after the flooding period.

In the solution culture experiment (Walter, Heuberger & Schnitzler 2004), cucumber seedlings were grown in 3 L-cylindrical plastic vessels and the treatments consisted of (i) aeration with pressurized air (21% ambient oxygen concentration) from 7 am to 9 pm for seven days, (ii) 0.4 mM H_2O_2 in the nutrient solution (resulting in oxygen concentration of $0.4 \times \frac{1}{2}(32) = 6.4$ mg L^{-1}), and (iii) a non-aerated oxygen-free control. The concentration of oxygen in the nutrient solution invariably stayed at nearly full saturation (i.e. 100% saturation) for the aerated treatment with pressurised air and about 0% for the control (i.e. non-aerated). After onset of irrigation, the concentration of O_2 rose to 120% saturation in the H_2O_2 treatment. The adventitious roots developed in the non-aerated control grew above the water surface. By contrast, no growth of adventitious roots was observed in the H_2O_2 or in the pressurized air treatment. It was claimed that adventitious roots occur only when oxygen content drops below a critical level and consequently the non-aerated control formed adventitious roots, to a greater or lesser extent, while the oxygenated treatments (H_2O_2 and pressurized air) failed to do so. In addition, the normal development of roots in the treatment aerated with hydrogen peroxide was significantly reduced. They proposed two possible factors responsible for this outcome: a) the O_2 level in the solution was adequate for the function and growth of the roots and there was simply no need to develop adventitious roots or, b) development of adventitious roots was prevented by H_2O_2. Moreover, in spite of the fact that the total amount of oxygen in the hydrogen peroxide treatment was about 100% saturation during the day, shoot growth was significantly slowed down and roots died compared to the pressurized air treatment. Quite clearly, conditions in the H_2O_2 treatment were not adequate for optimum growth and root functioning in any of the plant species. Therefore, they concluded that hydrogen peroxide in a concentration of 0.00136% (equal to 0.4 mM) in nutrient solution suppressed the root growth.

Recently, the response of plants grown in solution culture with oxygen concentrations above the saturation levels has been investigated by some researchers. Bonachela, Vargas and Acuna (2005) examined the effectiveness of increasing the amount of oxygen dissolved in a nutrient solution to hyper-saturation levels on watermelon grown in perlite bags (<5 mm particle size) in a greenhouse. Average oxygen values throughout the whole growing season, measured at the dripper outflow for the oxygen-enriched (enriched by algal photosynthesis) and the standard irrigated treatments were 13.5 and 5.9 ppm, respectively. They found no significant differences in growth, productivity and quality of the watermelon crops between the treatments. Indeed, a more comprehensive study is required to accurately determine the effects of elevated rates of dissolved oxygen in nutrient solutions on crop components. However, it is likely that diffusion of air through the uncovered surface of the perlite bags had negated the difference between the treatments.

Notwithstanding the results obtained by Bonachela, Vargas and Acuna (2005), Holtman et al. (2005) have shown that there is a direct relationship between plant growth and dissolved oxygen concentration levels in a continuous flow of nutrient solution for cucumber grown on rock wool blocks. They maintained the level of dissolved oxygen concentrations at 0.5, 3.5, and 6.0 mg L^{-1} inside the substrate blocks, where 0.5 mg L^{-1} represents a situation of anoxia, 3.5 mg L^{-1} represents about critical oxygen levels, and 6 mg L^{-1} is most likely a situation with sufficient oxygen to supply of the demand by root systems. They noticed that leaf area was greatest for the highest oxygen level in the nutrient solution.

Despite the apparent importance of root zone aeration on the functioning of plants, aeration techniques based upon direct delivery of compressed air to the root zone are not applicable at the field scale because of the chimney effect which causes the compressed air to escape from the soil at the point of injection. Recently, venturi air injectors have been designed and produced which draw air, instead of the conventional solution, into pressurized in-line SDI systems (Goorahoo et al. 2002). This technique of incorporating air into irrigation water for aeration of the root zone is known as 'Oxygation' or 'AirJection Irrigation'. When pressurized water passes through the throat of a venturi, its pressure decreases while its velocity increases (Bernoulli's principle). The reduction in the water pressure at the throat of the venturi (connected to the ambient air) causes air to be drawn into water (Figure 2.1). In this manner, air in the form of bubbles is introduced to the irrigation stream.

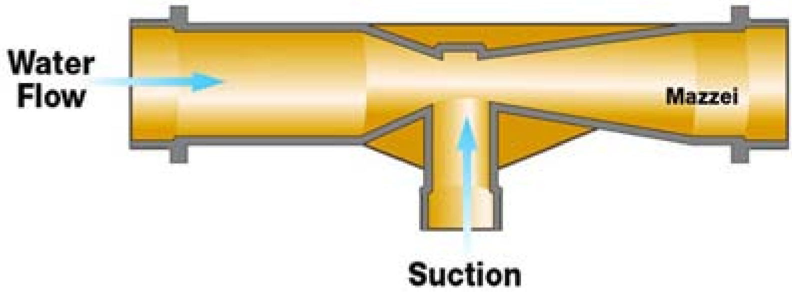

Figure 2. 1 A venturi air injector (Source: Mazzei Injector Corp., USA).

Goorahoo et al. (2002) conducted a field trial on green bell peppers to examine the impact of aerated irrigation water by means of a venturi air injector in a SDI system (hereafter called 'oxygation' as compared to chemigation or fertigation when chemicals or fertilizers are incorporated to irrigation water). The average aeration rate in each irrigation event, defined as the ratio of the measured flow rate of air to the measured flow rate of water multiplied by 100, was 12%. The result of their experiment in a fine sandy loam irrigated with 57 m long laterals indicated a 39% increase in the weight, and a 33% increase in the number of bell peppers in the aerated treatment compared with the non-aerated one. Moreover, significant increases in the shoots and root dry weights were observed from aerated plants compared to those in the control treatment. However, it was found that there was increased production (particularly in the number of bell peppers) from the beginning of the row to a maximum value at the 25 m location (i.e. the first 43% of the total lateral length). Then, a decrease in yield was observed down the row to a minimum value at the 51 m location (i.e. the first 88% of the total lateral length), and thenceforth the yield did not significantly differ from the yield of the control harvested over the corresponding distance.

Bhattarai, Huber and Midmore (2004) studied the effects of aeration of irrigation water by means of hydrogen peroxide (H_2O_2) and venturi on zucchini, cotton, and vegetable soybean on a fine textured soil in the field, as well as in pot trials. For zucchini in the field trial with imposed flooding of 18-h duration, they found a 25%, 29%, and 24% increase in fruit yield, number and shoot weight in the H_2O_2 treatment compared to the control. Vegetable soybean in the pot experiment showed a significant increase in fresh pod yield compared to the control treatment. The increase due to H_2O_2 and venturi were 82% and 96%, respectively. The corresponding increases in cotton lint were 14% and 28%, respectively. More recently, Bhattarai, Pendergast and Midmore (2006) investigated the impact of oxygation on water use efficiency (WUE) and fruit yield of tomato plants grown in a protected environment. They conducted two sets of experiments with venturi oxygation interacting with different soil moistures and different levels of irrigation water salinities in separate experiments under protected conditions. Compared with the corresponding non-aerated treatments, fruit yields influenced by aeration in the moisture and salinity treatments were increased by 21% and 38%, respectively. Furthermore, biomass WUE was greater by 32% and 16% in the salinity and moisture experiments, respectively.

Su and Midmore (2005) extended McWhorter's one-dimensional equation for the concurrent flow of air and water (CEFAW) to three dimensions and derived explicit steady and unsteady solutions to the CEFAW. The solutions provide appropriate means for analysis of water movement through soil profile either from a point source or a line source SDI. The equations can be used for a wide range of soil type, aeration rate, emitter discharge, and depth of installation of emitters.

Evidently, aeration of the root zone for most species grown on soil or in solution culture results in enhanced growth of roots and shoots. Also, application of other sources of oxygen supply, such as ozone and hydrogen peroxide showed beneficial effects on the root growth and plant performance. It is worthwhile to examine other techniques of oxygen supply to the root zone. Recently, Scott et al. (2008) employed a patented technology manufactured by Seair™ Diffusion Systems Incorporation to reduce the oil sands process water toxicity polluted from naphthenic acids. Filtered process water samples of approximately 100 L volume were introduced into a Seair gas/liquid diffusion system (model no. SA28). Air was conveyed through an oxygen concentrator and the extracted oxygen was then conveyed through the ozone generator. Ozone was supplied to the diffusion system, to obtain micro-bubbles (5 μm) of ozone. The concentration of dissolved ozone in the reactor was nearly 35 mg L^{-1}. The results indicated that ozonation of process water for 50 min generated a non-toxic effluent and decreased the concentration of naphthenic acids by ~70%. After 130 min of ozonation, the residual naphthenic acids concentration was 2 mg L^{-1}, which was less than 5% of the initial concentration in the filtered process water. These results suggest that the Seair diffusion system with air delivered as 5 μm micro-bubbles could be used as an alternative to the Mazzei air injection technique for aeration of plant roots.

In conclusion, aeration of rhizosphere enhances root activity and plant growth mainly through improved water and nutrient uptake, particularly in anaerobic conditions. However, for a given level of dissolved oxygen, some species show better responses. Soil aeration via injection of air alone through an SDI system is not efficient because the majority of the emitted air will move vertically above the emitter outlet directly toward the soil surface. Three major methods to avoid the disadvantages of the chimney effect are utilization of ozonated water, injection of hydrogen peroxide, and injection of air into irrigation water in a subsurface drip irrigation system employing the venturi principle. Ozone is a very powerful oxidizing agent and may oxidize plant residues and soil organic matter, thus enhancing availability of essential nutrients to plant roots. Nonetheless, further understanding of the effects of ozonated water on soil physical and chemical properties and on soil microorganisms is required. The solubility of hydrogen peroxide in water is far higher than that of pressurized air or molecular oxygen. However, the potential toxicity of peroxides to soil biota and their unpredictable rate of disproportion and decomposition when applied to soil is a limiting factor in the broader use of hydrogen peroxide in root zone aeration. Based on the venturi principle, irrigation water is over-aerated before it is delivered to the subsurface laterals. Oxygen concentration in the aerated water depends upon the temperature and pressure differential across the venturi. The main disadvantage of this method is the limited solubility of oxygen in water, which varies with water temperature, concentration of dissolved salts, and oxygen pressure in the air. Hence, the majority of the entrained air into water will be in the form of air bubbles, which in turn will result in non-uniform (declining) distribution of air bubbles along the laterals.

Chapter 3: Exploring the effect of various factors on the uniformity of emitter air flow rates along drip irrigation laterals

ABSTRACT

The objective of this study was to explore the effect of a variety of factors consisting of emitter cross sectional area, connector geometry and length, pipe diameter, surfactant, goof plug, and emitter type (pressure compensated vs. non-pressure compensated) on the distribution of emitter air flow rate along a lateral irrigation pipe. It was shown that 140% reduction in the magnitude of emitter cross sectional area caused 242% reduction in the water flow rate, whereas the corresponding reduction in the emitter air flow rate was 59% and statistically non-significant.

For symmetric connectors (i.e. the protruded part of the connector is in the shape of a truncated cone), delivery of air bubbles along the pipe directly depended upon the submerged length of the connector in the air layer flowing at the top of the pipe. Emitters with asymmetric connectors (i.e. the delivery opening in the connector is slanted and facing away from the direction of water flow) generally yielded greater air flow rates compared to those with symmetric ones, probably because of local turbulence at the tip of the connector, together with the submerged length of the connector. Moreover, for symmetric connectors, an increase in the pipe diameter was directly related to an increase in the uniformity of the distribution of the emitter air flow rate expressed by Christiansen's uniformity coefficient (CUC), and inversely related to the efficiency of air bubble delivery and mean emitter air flow rate. Contrary to the symmetric connectors, an increase in the pipe diameter was

associated with a decrease in CUC, but caused an increase in efficiency of air bubble delivery and mean emitter air flow rate for asymmetric connectors.

As the concentration of a nonionic surfactant was increased in the irrigation water, the efficiency of air bubble delivery, the mean emitter air flow rate, maximum emitter air flow rate, and consequently the range of emitter air flow rates were decreased. CUC was enhanced by 60% when the final concentration of surfactant in the irrigation water reached 1.2 ppm, whereas the minimum air flow rate did not show a consistent response.

The extraordinary high air flow rate observed in the first few emitters of the integral dripper line or pot drippers with asymmetric connectors caused a drop off in the water flow rate. Insertion of goof plugs before the symmetric and asymmetric connectors improved the CUC of the emitter air flow rates by 17% and 18%, respectively, whereas the addition of surfactant at a final concentration of 32 ppm to the irrigation water for the foregoing connectors (without goof plugs) enhanced the CUC by 22% and 119%, respectively. Furthermore, it was postulated that addition of surfactant enhanced the CUC values through an increase in the number of air bubbles in the irrigation pipe, whereas insertion of goof plugs immediately before the symmetric connectors improved availability of air bubbles to the remote emitters. Regardless of the type of connectors, the highest CUC was obtained when both goof plugs and surfactant were used.

3.1 Introduction

Subsurface drip irrigation (SDI) in common with other methods of irrigation is liable to expel soil air around the root zone during and following irrigation events, thereby impairing root function and crop performance (Bhattarai, Su & Midmore

2005). It has been shown that SDI has the capability for providing the root zone with oxygen by coupling an air injector venturi to the pressurized irrigation line (Goorahoo et al. 2002).

Although root zone aeration by means of air injector venturi in SDI systems has led to significant enhancement in the growth parameters for a number of plant species (Bhattarai, Huber & Midmore 2004; Bhattarai, Su & Midmore 2005; Bhattarai, Midmore & Pendergast 2008; Goorahoo et al. 2007a; Essah, Delgado & Davidson 2009) little is known about the distribution of air bubbles along a lateral pipe and the factors that may influence the availability of the bubbles to the emitters. Goorahoo et al. (2002) reported a non-uniform declining trend along the irrigation lateral in the number as well as the weight of bell peppers grown using an air injector SDI system. Similar non-uniformity has been recorded for the yield of aerated tomatoes irrigated from the upstream end of the lateral (higher yield) compared to those located at the downstream end (lower yield) of the pipe (Goorahoo et al. 2007b).

Concurrent flow of air and water in a pipe is a type of two-phase flow. Razzaque et al. (2003) studied the distribution of air bubble size in a horizontal flow of an air-water system. In their experiment, an air supply line (2 or 4 mm internal diameter (ID) stainless steel tube) was connected to a horizontal flow loop (25.4 mm ID) through a T-junction. Due to the low velocity of water (1-3 m s^{-1}) and small diameter of bubbles at the beginning of the experiment, coalescence, not breakage, played the dominant role in determining bubble size (by means of a high speed charge-coupled camera) in the study. As the bubbles travelled downstream, their diameter increased due to coalescence.

Tshuva, Barnea and Taitel (1999) studied two-phase flow in two inclined parallel Plexiglas pipes of 24 mm diameter and 3 m length with common inlet and outlet manifolds. There were no outlets (e.g. emitters) on either of the branching pipes. The range of superficial velocities for air and water was 0.15-5.6 m s^{-1} and 0.02-3.03 m s^{-1}, respectively. The test was performed for a wide range of inclination angles from 0-90º. It was shown that depending on the pipe inclination and the ratio of air to water flow, the flow distribution into the pipes can be either symmetric (i.e. two-phase flow in both pipes) or asymmetric (i.e. two-phase flow in one pipe and water only in the other one). For the horizontal case, the flow was symmetric for all flow conditions. The asymmetric flow was observed in upward inclined parallel pipes at low gas and liquid flow rates. For high liquid and/or gas flow rates, the air and water flow was symmetric as for the case of horizontal flow.

The movement of air bubbles depends mainly on the buoyancy and the drag forces. Since these forces act in the opposite direction in a downwardly inclined pipe, bubbles either move upward or downward. The direction depends mainly on the pipe slope, the water velocity, and the bubble volume and shape. Glauser and Wickenhauser (2009) investigated the movement of non-spherical bubbles of a height larger than 5 mm along a 11 m long pipe of 48 mm diameter at an average velocity ranging 0.54-1.36 m s^{-1}. Pipe slope ranged from 0.017 to 0.087 (i.e. 1.7-8.7%) and the pressure was maintained at 1 MPa (145 psi). It was found that for a given water velocity and pipe slope, there is a critical bubble volume at which the bubble is stagnant (equilibrium between the buoyancy and drag forces). Bubbles with a volume larger than the critical bubble volume move upward (domination of the buoyancy force over drag) and bubbles with a volume smaller than the critical bubble volume move downward (domination of the drag force over buoyancy).

Addition of surfactant to water results in reduction in water surface tension and causes pressure drop per unit length of a pipe (Rosenblit et al. 2006). Visual observations of flow patterns in vertical upward air-water flow showed that the addition of surfactant led to a significant reduction in the tendency of coalescence between air bubbles. Also, compared to a pure air-water mixture, addition of surfactant increased the number of air bubbles but reduced their diameter (Rosenblit et al. 2006).

The objectives of this study were to explore the effect of a number of factors including emitter cross sectional area, pipe diameter, geometry of connectors, goof plugs, piping layout, and concentration of surfactant on the distribution of emitter air flow rates in recirculating and dead-end irrigation systems.

3.2 Materials and Methods

3.2.1 Trials in a recirculating drip irrigation system

3.2.1.1 Pipe diameter, cross sectional area of emitter, and connector type

The irrigation system consisted of a 200 L water tank, a Davey™ pump[1] model V312L, a by-pass pipe with a gate valve for adjustment of the inlet pressure to a venturi, and two pressure gauges at the inlet and outlet of the venturi for monitoring the set pressures (Figure 3.1). A pressure gauge followed by a gate valve was connected at the end of the irrigation pipe before the water tank to maintain the set pressure at the outlet of the venturi and sustain the minimum operating pressure required for the remote emitters. The inlet and outlet pressure at the air injection

[1] The use of product names in this research is not an endorsement of the company's product. These names are mentioned here primarily for the purpose of letting readers know where the relevant materials can be obtained.

venturi and the pressure at the end of the irrigation pipe were 345, 103, and 69 kPa (50, 15, and 10 psi) respectively.

Figure 3. 1 Experimental layout for trials described in section 3.2.1.

The characteristics of trials designed to study the effects of emitter cross sectional area, pipe diameter, and connector type (trial 1), the effect of surfactant concentrations (trial 2), and preferential path for air flow (trial 3) are summarised in Table 3.1. Two types of Netafim™ pressure compensated 'PCJ' on-line drippers, one of 0.52 mm^2 cross sectional area (CSA) and the other of 1.25 mm^2 CSA, were tested and the data were analysed by paired t-test. Asymmetric connectors (Figure 3.2) were used for the trials involving the effect of CSA on the uniformity of air flow rate distribution. The drippers were spaced 50 cm apart with the first dripper 1.5 m from the venturi. The nominal water flow rate of the small CSA and the large CSA emitters was 1.2 and 4.0 L h^{-1}, respectively, under operating pressure range of 50 - 400 kPa (7-58 psi).

To explore the effect of pipe internal diameter on the distribution of air flow

Table 3. 1 Characteristics of the different trials in a recirculating irrigation system.

Trial No. (Section)	Pipe ID (mm)	Emitter Type		Connector type and protruded length (mm)	Final concentration of surfactant (ppm)	Injector type
		CSA (mm^2)	Water flow rate (L h^{-1})			
1 (3.2.1.1)	13, 19, 25	0.52, 1.25	1.2, 4.0	Asymmetric (9.5 mm), Symmetric (9.5 mm)	-	Netafim venturi model F3/4-0.9
2 (3.2.1.2)	19	0.52	1.2	Asymmetric (9.5 mm)	0.3, 0.5, 0.7, 1.0, 1.2	Netafim venturi model F3/4-0.9
3 (3.2.1.3)	19 mm (main pipe and manifold), 13 mm (lateral pipe)	Data not available	1.1	Symmetric (7 mm)	-	Mazzei venturi model 384

along the lateral line, 17 m long low density polyethylene irrigation pipes of three differing internal diameters 13, 19, and 25 mm were used in these trials with five replications over time. The irrigation pipe was laid on level benches in the test area. This pipe was laid out in a ‘U’ shape configuration on a bench area of 25 m^2 being 2.5 m by 10 m. The irrigation water was recirculated in a closed circuit from the water tank to the oxygation system. In other words, water was pumped from the tank, and flowed in the irrigation pipe where part of the water (and air) was discharged through the emitters and the remainder returned to the tank.

Two types of connectors were tested: asymmetric (Figure 3.2) and symmetric (Figure 3.3). One end of each connector was inserted into the pipe and the other end was connected to the dripper by means of a 50 cm long riser tube of 4 mm diameter. The length of the symmetric and asymmetric connectors protruding inside the pipe was 9.5 mm. Each riser tube was equipped with a tap to control the flow of air and water from the emitter.

To estimate air delivery from each emitter, a 0.55 L plastic bottle full of

Figure 3. 2 An asymmetric connector. These connectors are inserted into irrigation pipe with the high end upstream.

Figure 3. 3 A symmetric connector.

water was inverted into a pot filled with water. The immersed bottle was devoid of air bubbles prior to starting the measurements. When an emitter was put into the inverted bottle, the discharged air bubbles displaced water and accumulated within the inverted bottle. The volume of the discharged air bubbles (ignoring the volume of the suspending micro bubbles) was equal to that of the displaced water. The air flow rate was calculated as the volume of the air (the difference between the volume of water remaining in the bottle and the full volume of the bottle) divided by the time period (90 seconds for each emitter) when air bubbles were collected. The volume of water was measured with a 1000 mL measuring cylinder. The accuracy of the measuring cylinder was ±10 mL at 20 °C.

In addition to air flow rate, water flow rates from each emitter, efficiency of air bubble delivery, and Christiansen’s uniformity coefficient (CUC) for air flow rates were measured. To measure emitter water flow rate, the volume of water delivered within a given time (6 to 10 minutes) was measured, following collection of water in the same bottles used for measuring the emitter air flow rates. The collected volume of water was measured with a 1000 mL measuring cylinder and divided by the sampling time. Efficiency of air bubble delivery (AE), expressed in percentage, is defined as the ratio of the sum of air flow rates discharged by the emitters to the air flow rate supplied at the outlet of the air injector venturi. For every trial, to calculate the sum of air flow rates from emitters, first the taps on riser tubes were shut so that no water or air passed through the emitters. Hence, the entire air volume supplied by the venturi could be collected at the end of the irrigation pipe. To collect the air bubbles, the end of the pipe was put into an inverted 5000 mL measuring cylinder full of water, held within a tank full of water. At the end of a time period, the bottom of the measuring jug was partially lifted above the water surface in the tank in order to read the volume of the collected air. The procedure was repeated five times and then the measurements were averaged. Next, all the taps were opened and air flow rate at the end of the pipe was again measured with the same procedure as above. This measurement was replicated five times and the results averaged. The difference between these average values is the sum of air flow rates which were discharged from the emitters (ignoring the volume of suspending micro bubbles in the measuring jug).

CUC was used as a measure of uniformity of air flow rate distribution along the irrigation pipe. It is calculated by the following equation (Stewart & Howell 2003):

$$CUC = \left(1 - \frac{D}{M}\right) \times 100 \tag{3.1}$$

where:

CUC = Christiansen's coefficient of uniformity (%)

D = average of the absolute values of the deviation from the mean air flow rates

$$= \frac{1}{n}\sum_{i=1}^{n} \left| X_i - M \right| \tag{3.2}$$

X_i = emitter flow rate

n = number of measured flow rate values

M = average of air flow rate values

$$= \frac{1}{n}\sum_{i=1}^{n} X_i \tag{3.3}$$

3.2.1.2 The effect of different concentrations of surfactant on the uniformity of emitter air flow rates

To study the effect of different concentrations of surfactant on the uniformity of emitter air flow rates (Table 3.1, trial 2), the same layout and apparatus as described in the beginning of this section were used except that the following amendments were made. For injection of surfactant into the irrigation pipe, a Netafim™ venturi model F3/4-0.9 was inserted in-between the by-pass pipe and the air injector venturi. Figure 3.4 shows the position of the chemical injector venturi in the irrigation system. The pressures at the inlet and outlet of chemical injector venturi were 476 and 303 kPa (69 and 44 psi), respectively. For the air injector venturi, the inlet and outlet pressures were 303 and 90 kPa (44 and 13 psi), respectively. The pressure at the end of the pipe was 69 kPa (10 psi).

The length and internal diameter of the irrigation pipe were 17 m and 19 mm, respectively. The end of the irrigation pipe was put into a drainage channel and free flow of water into the channel was maintained. Asymmetric connectors and Netafim™ pressure compensated 1.2 L h^{-1} on-line drippers were used. The operating pressure range for the emitters was 50-400 kPa (7-58 psi). Water flow rate at the beginning of the irrigation pipe was close to 960 L h^{-1}.

Alcohol alkoxylate, a biodegradable non-ionic surfactant sold as BS 1000™, was used in these trials. With respect to surface tension, critical micelle

Figure 3. 4 The position of the chemical injector venturi in the irrigation system.

concentration is one of the main parameters used to characterize the surfactant activity in solutions (Lee et al. 2002).

Critical micelle concentration is defined as the concentration above which micelles form (Dominguez et al. 1997). A formal critical micelle concentration measurement was not available for BS 1000™, but it is likely to be in the range of 1-5×10^{-3} gL^{-1} (personal communication with Andrew F. Kirby, Global Technology Manager at Crop Care Australia Pty Ltd.). Surfactant was diluted to 20, 35, 50, 65, and 80 ppm before being injected into the irrigation system. The diluted surfactant was injected through the irrigation pipe at a rate of 14.4 mL h^{-1}. Air flow rate as well as water flow rate as affected by these surfactant concentrations were measured as described earlier in this section, and compared with the average air flow rate or water flow rate obtained in the absence of surfactant in the line.

Injection of a chemical at a given rate into an irrigation system will result in further dilution of the chemical. The final concentration of the chemical throughout the irrigation pipe (C_f) and the time when this occurs (T) is estimated by the following equations:

$$C_f = \frac{IR \times C_i}{Q} \tag{3.4}$$

$$T = \frac{\left(\frac{\pi d^2}{4}\right) \times L \times 0.06}{Q} \tag{3.5}$$

where:

C_f = Final concentration of the chemical throughout the pipe, in ppm

IR = Chemical injection rate, in L h^{-1}

C_i = Concentration of chemical in the solution to be injected, in ppm

Q = Water flow rate at the beginning of the pipe, L h^{-1}

0.06 = A unit conversion factor to get the time in minutes

T = Time to have the final concentration of the injected chemical everywhere throughout the irrigation pipe, in min

d = Internal diameter of the irrigation pipe, in mm

L = Length of the irrigation pipe, in m

Hence, about 20 seconds after the pump was switched on, the final concentration of surfactant for the foregoing initial concentrations became 0.3, 0.5, 0.7, 1.0, and 1.2 ppm, respectively.

3.2.1.3 Preferential path for air flow

Four different types of tubing layouts (Figures 3.5-3.8) were tested to explore whether air bubbles follow a preferential path in a recirculating irrigation system (Table 3.1, trial 3). The lateral pipes were comprised of three parts. The first 50 cm of the pipe was connected to the inlet manifold at a 50º upward slope. The middle part was 8 m long, laid flat on a supporting surface and contained two emitters at either end. The last part was 50 cm long and was connected to the outlet manifold at a 50º down slope. For each layout only one measurement was taken and then the flow rates on each lateral were averaged. Short symmetric connectors (7 mm long) and 1.1 L h^{-1} Plastro™ pressure compensated emitters were used in these trials. Air was introduced into the system by means of a Mazzei™ air injector venturi model 384. The inlet and outlet pressures across the venturi were 414 kPa (60 psi) and 76 kPa (11 psi), respectively. The pressure at the end of the pipe, before entering into the water tank was maintained at 62 kPa (9 psi).

3.2.2 Different connectors and emitters, with surfactant or goof plug in dead-end drip irrigation systems

The irrigation pipe was laid spirally (constituting four coils for trials with pot drippers or five coils for trials with an integral dripperline) on levelled benches with a circular configuration. The average radius of the coils was approximately 8 m resulting in formation of a smooth curvature around the corners of the benches (Figure 3.9). The length of each coil was approximately 50 m with four sampling locations in each coil distributed evenly along the irrigation pipe in addition to the first and last sampling locations. Each sampling location consisted of three consecutive emitters. The first and the last three consecutive emitters on the irrigation pipe formed the first and the last sampling locations, respectively. At each sampling point, emitter water or air flow rates were measured as described in section

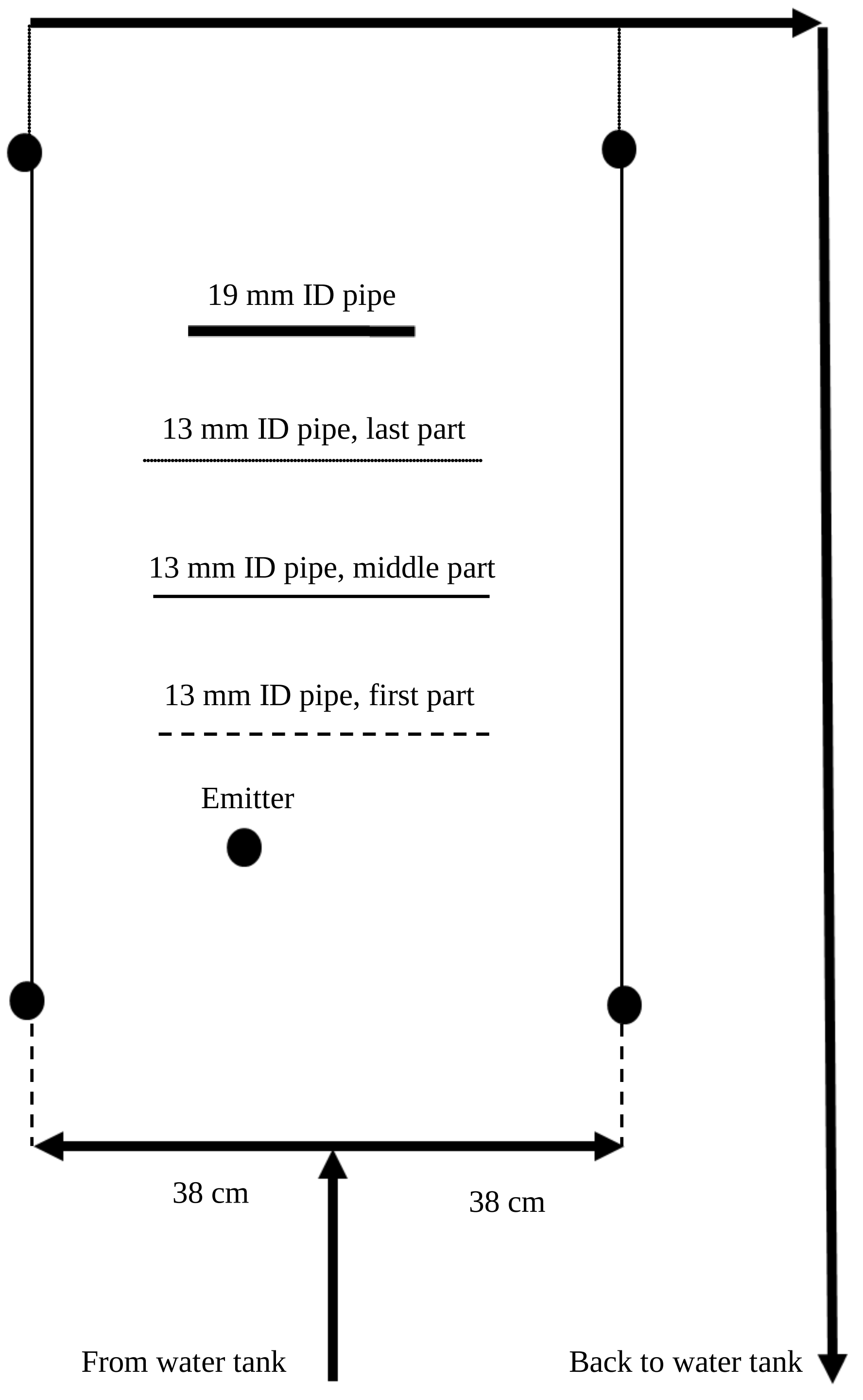

Figure 3. 5 Type A layout; sub-main (manifold) connected to two equidistant laterals.

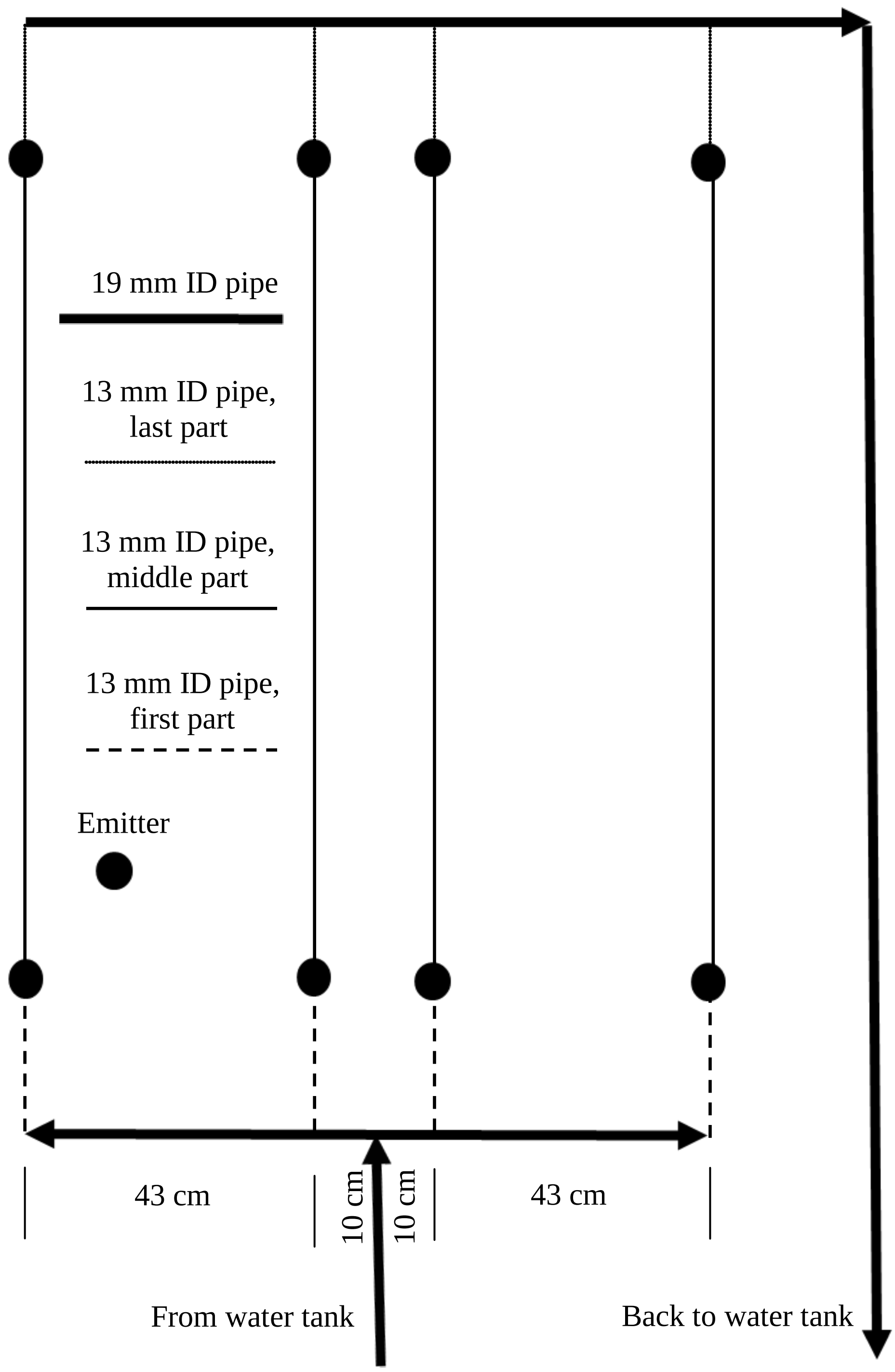

Figure 3. 6 Type B layout; sub-main connected to two pairs of unevenly spaced laterals.

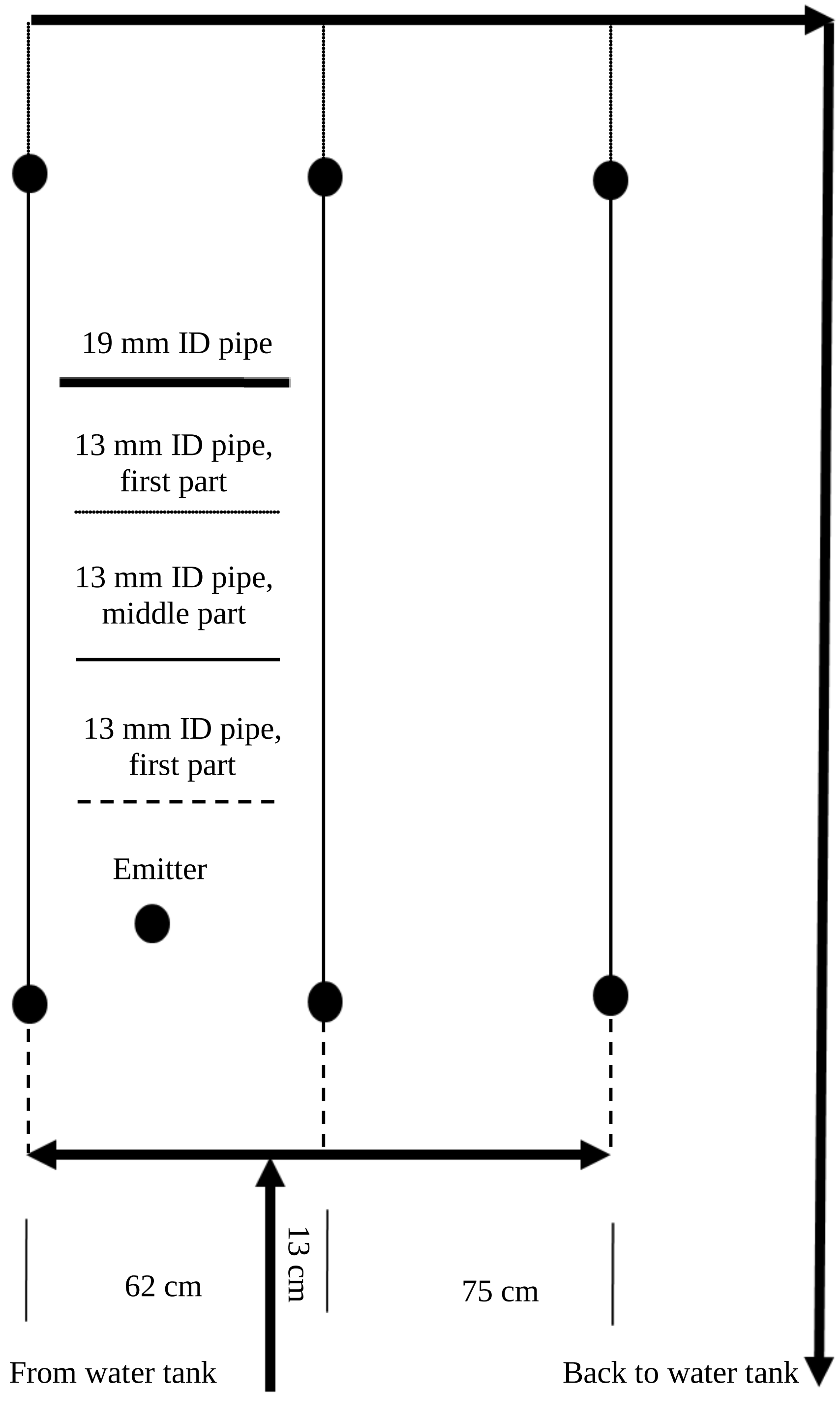

Figure 3. 7 Type C layout; sub-main connected to three unevenly spaced laterals.

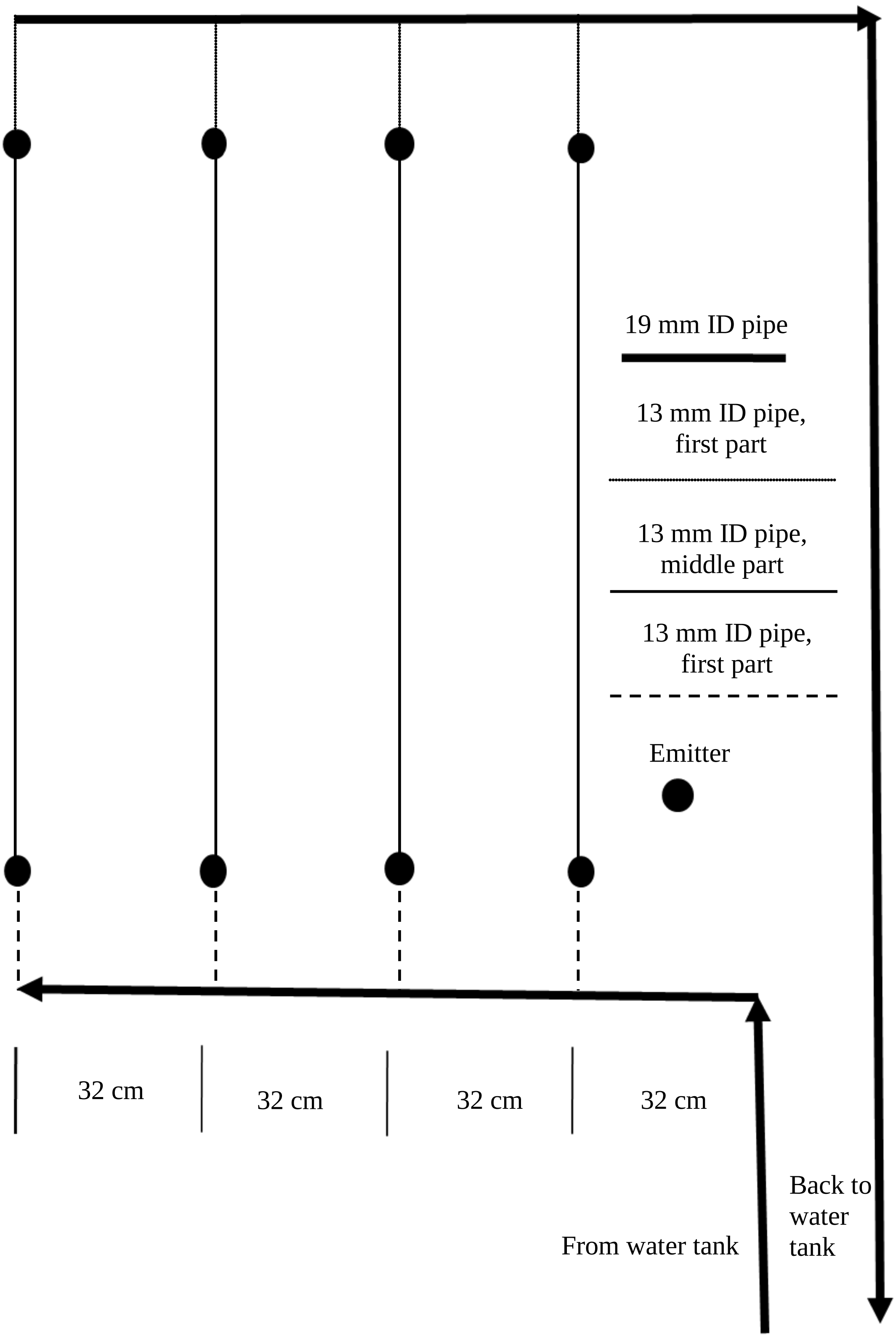

Figure 3. 8 Type D layout; sub-main serially connected to four equidistant laterals.

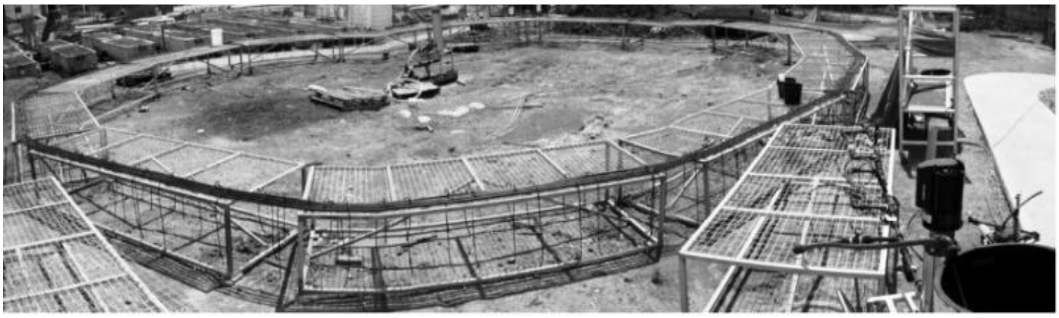

Figure 3. 9 The experimental layout for trials described in section 3.2.3.

3.2.1 and then averaged.

Netafim™ venturi model F3/4-0.9 or Mazzei™ venturi model 484 were used for injection of surfactant or air into the irrigation line, respectively. Measurements involving emitter water flow rates consisted of three trials. In the first trial, the suction port of both venturis was fully shut so that no chemical or air could be introduced into the irrigation system. In the second trial, only the suction port of the chemical injector venturi was fully shut while the air injector venturi was in operation. In this condition, emitter water flow rates as affected by air flow were measured. In the third trial, both venturis were working and water flow rates as affected by air flow and surfactant were measured at the sampling locations.

Measurement of air flow rates from emitters consisted of two trials. In the first trial, the suction port of the chemical injector venturi was fully shut and only the air injector venturi was working. In the second trial, both venturis were in operation. The average time for measurement of air flow rates at each sampling location was 35 minutes.

In trials with on-line pot drippers, a total of 768 drippers spaced at 25 cm along the irrigation pipe was used. The internal diameter and total length of the pipe were 19 mm and 195 m, respectively. The end of the irrigation pipe was equipped with a pressure gauge followed by a gate valve. The initial concentration of surfactant injected into the irrigation system (C_i) was 1000 ppm, the surfactant injection rate (IR) was 30 L h^{-1}, and water flow rate was 922 L h^{-1}, giving a final surfactant concentration (C_f) at 32 ppm. The gate valve remained fully shut during the experiments and pressure gauge was used to monitor the pressure at the end of the line to ensure that all the emitters in the irrigation system (particularly the remote ones) would be working within the operating pressure range recommended by the manufacturer. In all the following trials, to ensure stabilization of surfactant concentration everywhere within the pipe, emitter air or water measurements were commenced at least sixty minutes after switching on the pump. The pressures at the inlet and outlet of the chemical injection venturi were 723 and 414 kPa (105 and 60 psi), respectively. For the air injector venturi, the pressures at the inlet and outlet of the venturi were 414 and 138 kPa (60 and 20 psi), respectively. The pressure at the end of the line was 55 kPa (8 psi). A summary of the characteristics of the trials in a dead-end drip irrigation system is presented in Table 3.2.

Table 3. 2 Details of the trials in a dead-end irrigation system.

Trial No. (Section)	Emitter type	Emitter flow rate (L h^{-1})	Emitter spacing (cm)	Pipe diameter (mm)	Pipe length (m)	Connector type and length (mm)	Goof olug	Final surfactant concentration (ppm)	Air injector venturi
4 (3.2.2.1)	Pressure compensated pot dripper	1.2	25	19	195	Asymmetric 9.5 mm	With/ without	32	Mazzei model 484
5 (3.2.2.2)	Pressure compensated pot dripper	1.2	25	19	195	Symmetric 9.5 mm	With/ without	32	Mazzei model 484
6 (3.2.2.3)	Non-pressure compensated pot dripper	1.15	25	19	195	Symmetric 7.0 mm	without	32	Mazzei model 484
7 (3.2.2.4)	Non-pressure compensated drip tape	0.8	40	22.2	245	without	without	62	Mazzei model 384

3.2.2.1 Air flow rate distribution from pressure compensated on-line pot drippers with long (9.5 mm protruding length) asymmetric connectors (trial 4)

Netafim™ pot drippers model PCJ 1.2 L h^{-1} of operating pressure range 50 - 400 kPa (58-7 psi) were used in these trials. Air flow rate distribution was assessed under two conditions: injection of 30 L h^{-1} surfactant (C_f = 32 ppm), or insertion of a goof plug (Figure 3.10) immediately before every connector. Essentially, a goof plug (9.5 mm protruding length) is an asymmetric connector with one end (the one which is not inserted into the pipe) sealed.

Figure 3. 10 An asymmetric goof plug.

3.2.2.2 Air flow rate distribution from pressure compensated on-line pot drippers with long symmetric connectors (trial 5)

The trial was the same as trial 4, except that symmetric connectors similar to the one shown in Figure 3.3 were used. The length of these connectors inside the pipe was 9.5 mm. As in section 3.2.3.1, C_f was 32 ppm.

3.2.2.3 Air flow rate distribution from non-pressure compensated on-line pot drippers with short symmetric connectors (trial 6)

The trial was the same as trial 5, but with two differences: the emitters were Netafim™ non-pressure compensated 1.15 L h^{-1} (at 100 kPa or 14.5 psi water pressure) with a maximum operating pressure of 200 kPa (29 psi), and the protruding length of connectors inside the pipe was 7 mm (Figure 3.11). For non-pressure compensated drippers, the emitter flow rate is a function of pressure and varies along the irrigation pipe. So, it is more convenient to use aeration rate (the ratio of air to water flow) instead of the absolute rate of air flow per emitter. The aeration rate (expressed in %) for each emitter is calculated as the ratio of air to water flow rate multiplied by 100. In these trials, C_f was 32 ppm and only the effect of surfactant (presence or absence) on emitter water or air flow rates was explored. The pressures at the inlet and outlet of the chemical injection venturi were 793 and 469 kPa (115 and 68 psi), respectively. For the air injector venturi, the pressures at the inlet and outlet of the venturi were 469 and 193 kPa (68 and 28 psi), respectively. The pressure at the end of the line was 103 kPa (15 psi).

Figure 3. 11 A short symmetric connector.

3.2.2.4 Air flow rate distribution from a non-pressure compensated integral dripperline (trial 7)

In trials with non-pressure compensated integral dripperline, a Netafim™ dripperline, model ‘Python’ with non-pressure compensated emitters of 0.8 L h^{-1} at 100 kPa (14.5 psi) water pressure spaced at 40 cm was used. This was the same type of dipperline used by Pendergast and Midmore (2006) for oxygation of cotton. The maximum operating pressure for these emitters is 110 kPa (16 psi). The inside diameter and the wall thickness of the dripperline were 22.2 mm and 0.34 mm, respectively. The thickness of the emitter was 2 mm. Owing to the symmetry in the shape of the emitter, it could be regarded as a symmetric connector of 2 mm protruded length (Figure 3.12). The total number of emitters, the length of the dripperline, and the number of coils were 607, 245 m and 5, respectively. There were four sampling locations on each coil. Each sampling location consisted of three consecutive emitters (Figure 3.13). There were twenty sampling locations in total, the first location included the first three emitters and the last one included the last three emitters; the remaining sampling locations were evenly distributed along the line.

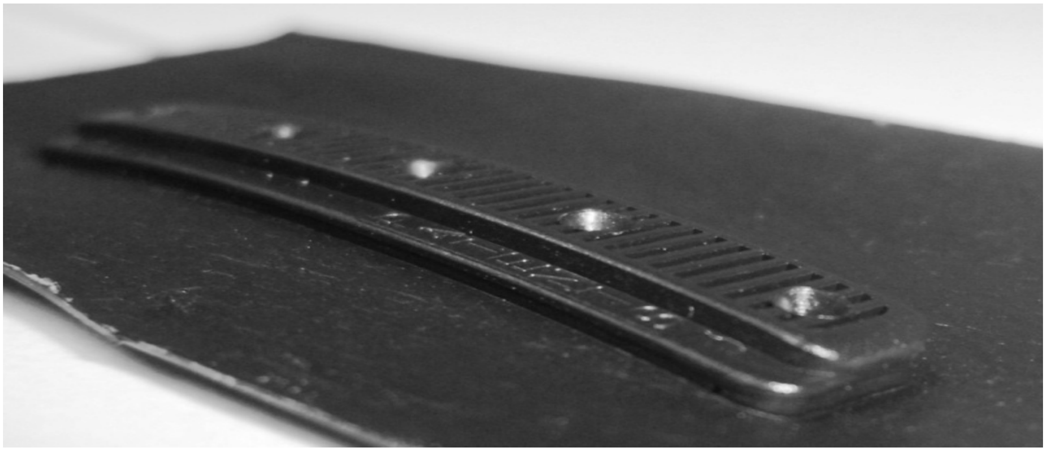

Figure 3. 12 A non-pressure compensated integral dripper.

Figure 3. 13 A sampling location consisting of three sampling points.

To collect water or air from an emitter, a piece of 45 mm long PVC tube of 27 mm internal diameter was connected to a 4 mm internal diameter riser tube of 50 cm length by a 100×4 mm barbed/threaded connector (Figures 3.14 and 3.15). At each sampling point, the emitter (faced upward) was surrounded by the PVC tube and hence a space formed therein.

Figure 3. 14 A threaded/barbed connector.

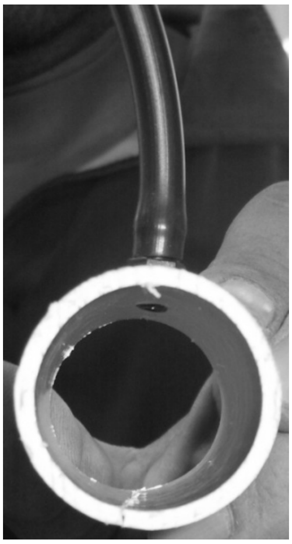

Figure 3. 15 A collector for air or water discharged from emitter on a dripperline.

The volume of the space was 7.8 mL. Both ends of the PVC tube were sealed by adhesive tape (Figure 3.16). Thus, the discharged water or air from the emitter accumulated in the enclosed space, then was directed through the riser tube and finally was collected in a plastic bottle.

For injection of surfactant into the line, Mazzei™ venturi model ‘A-3’ and for air injection, Mazzei™ model ‘384’ was used. Surfactant of initial concentration (C_i) of 1000 ppm was injected at a rate of 30 L h^{-1} into the line. In these trials, water flow rate at the beginning of the line was 480 L h^{-1}, hence C_f was 62 ppm. Since the emitters were non-pressure compensated, aeration rates were calculated for the sampling locations and analysed. The pressures at the inlet and outlet of the chemical injection venturi were 552 and 345 kPa (80 and 50 psi), respectively. For the air injector venturi, the pressures at the inlet and outlet of the venturi were 345 and 110

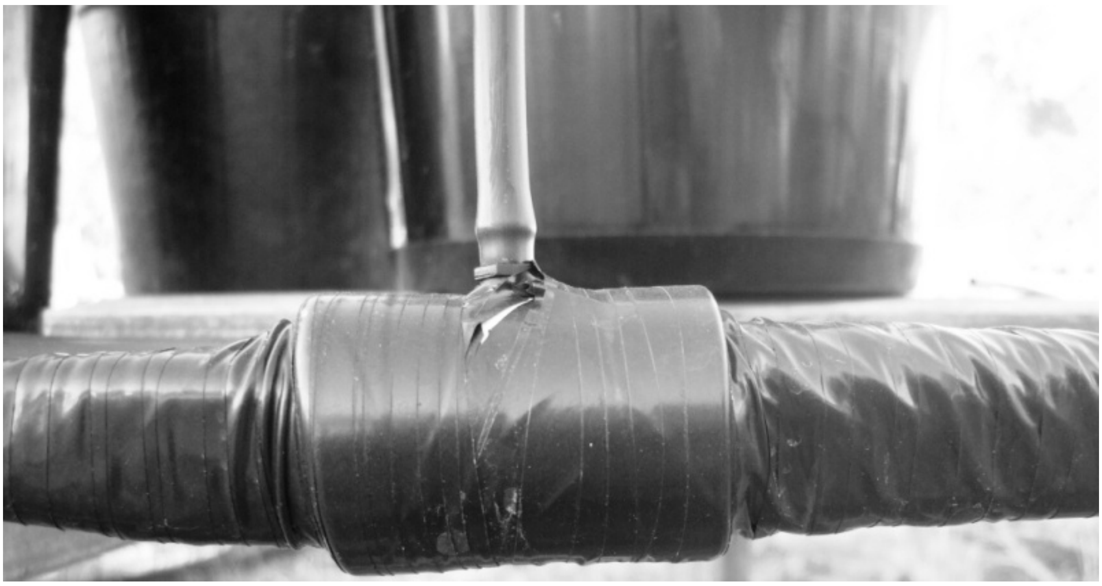

Figure 3. 16 A sealed collector on a dripperline.

kPa (50 and 16 psi), respectively. The pressure at the end of the line was 90 kPa (13 psi).

3.3 Results

3.3.1 The effect of CSA, pipe diameter, and geometry of connectors on the uniformity of air flow rates from emitters

A summary of the data is presented in Table 3.3. Clearly, the CSA of the emitters had no significant effect on the efficiency of air bubble delivery but the CUC of air flow rates for the emitters of small CSA was ten times better than that for the large ones. For each emitter type, the mean of the measured air flow rates were tested using a two-tailed paired t-test. The calculated t-test with df = 29 at $P<0.05$ was 3.592, indicating a significant difference between the airflow rates affected by the emitter CSAs. The air flow rate per emitter decreased rapidly with distance along the irrigation pipe, being relatively lower for the smaller CSA emitters (Fig. 3.17).

The distribution of air or water flow rates for each pipe diameter and connector geometry is shown in Figures 3.18-3.22. From Figure 3.18, air flow rates present two distinct

Table 3. 3 The effect of the connector geometry or pipe diameter on the distribution of emitter air flow rates and water flow rates. (Trial 1, section 3.2.1.1)

Connector geometry	Pipe diameter (mm)	Emitter CSA (mm^2)	CUC for air (%)	CUC for water (%)	AE (%)	Mean	
						Air flow rate (L h^{-1})	Water flow rate (L h^{-1})
Symmetric	13	1.25	-6	97	18	2.6	4.1
	19	1.25	11	97	13	2.3	4.1
	25	1.25	100	96	1	0.2	4.0
Asymmetric	13	1.25	19	96	92	4.5	4.0
	19	1.25	2	98	98	5.1	4.1
		0.52	20	93	98	3.2	1.2
	25	1.25	-1	96	100	5.3	4.0

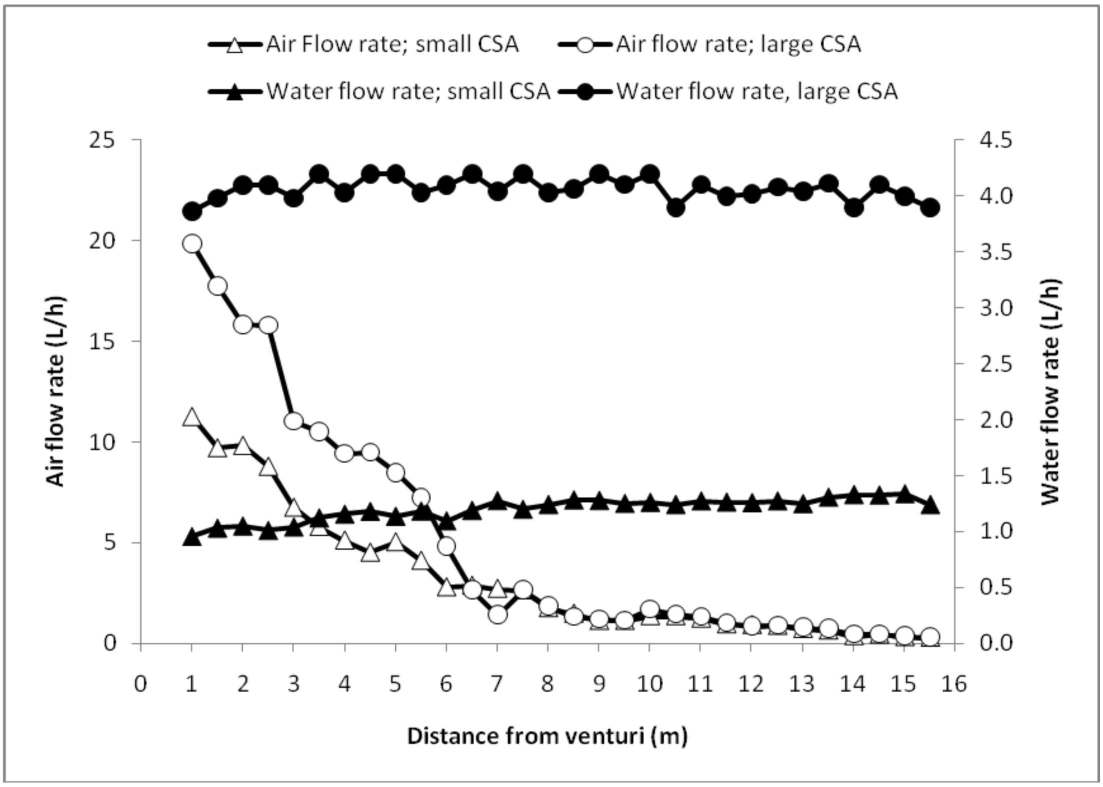

Figure 3. 17 The effect of pipe diameter on the emitter air flow rate distribution with symmetric connectors.

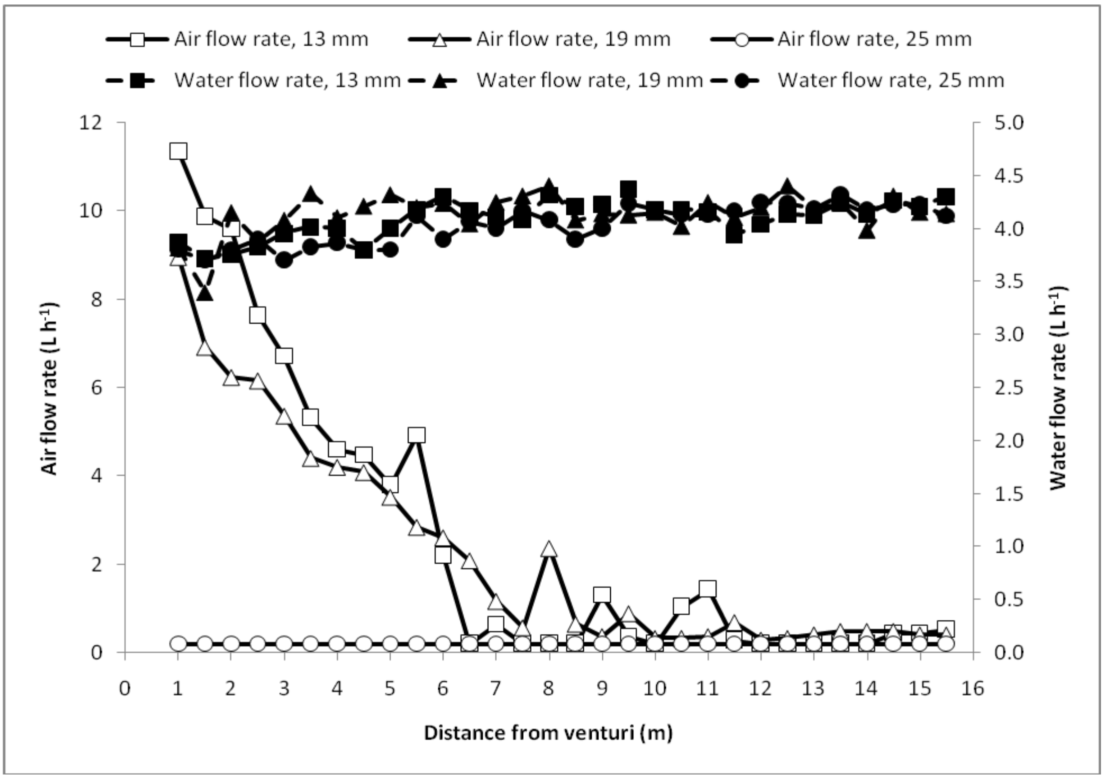

Figure 3. 18 The effect of pipe diameter on the emitter air flow rate distribution with symmetric connectors.

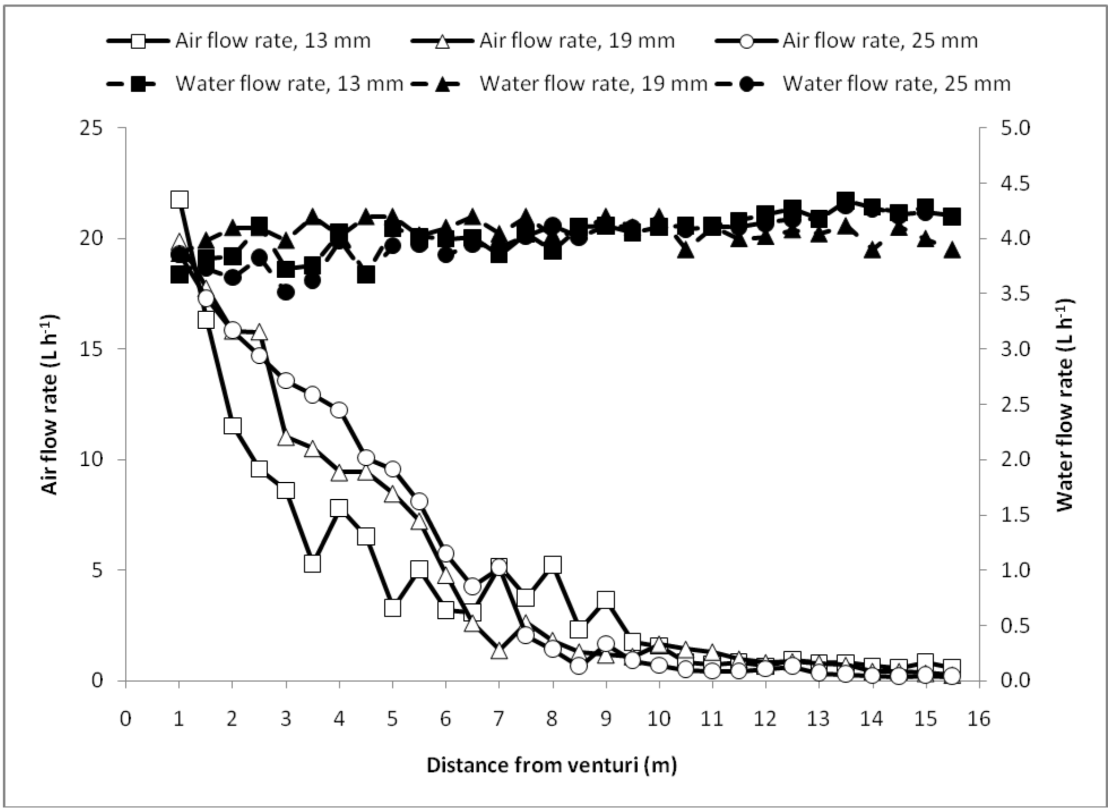

Figure 3. 19 The effect of pipe diameter on the emitter air flow rate distribution with asymmetric connectors.

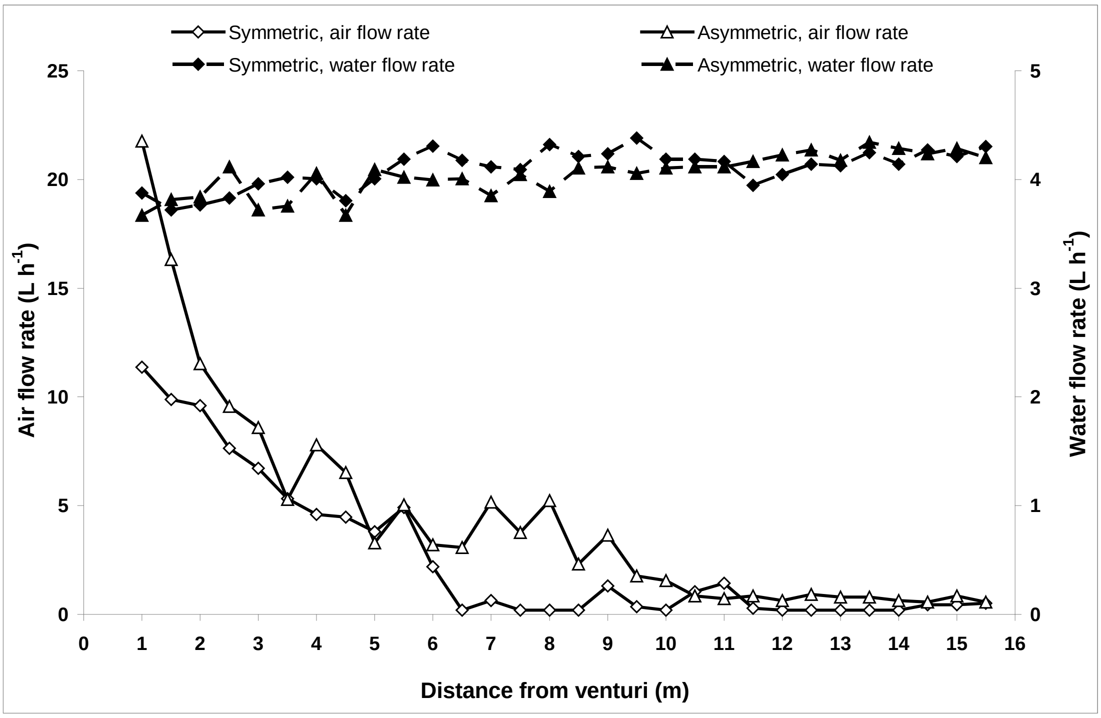

Figure 3. 20 The effect of connector geometry on the distribution of emitter air flow rates in a 13 mm ID irrigation pipe. (For asymmetric connectors, the same data for a 13 mm pipe from Figure 3.19 has been used.)

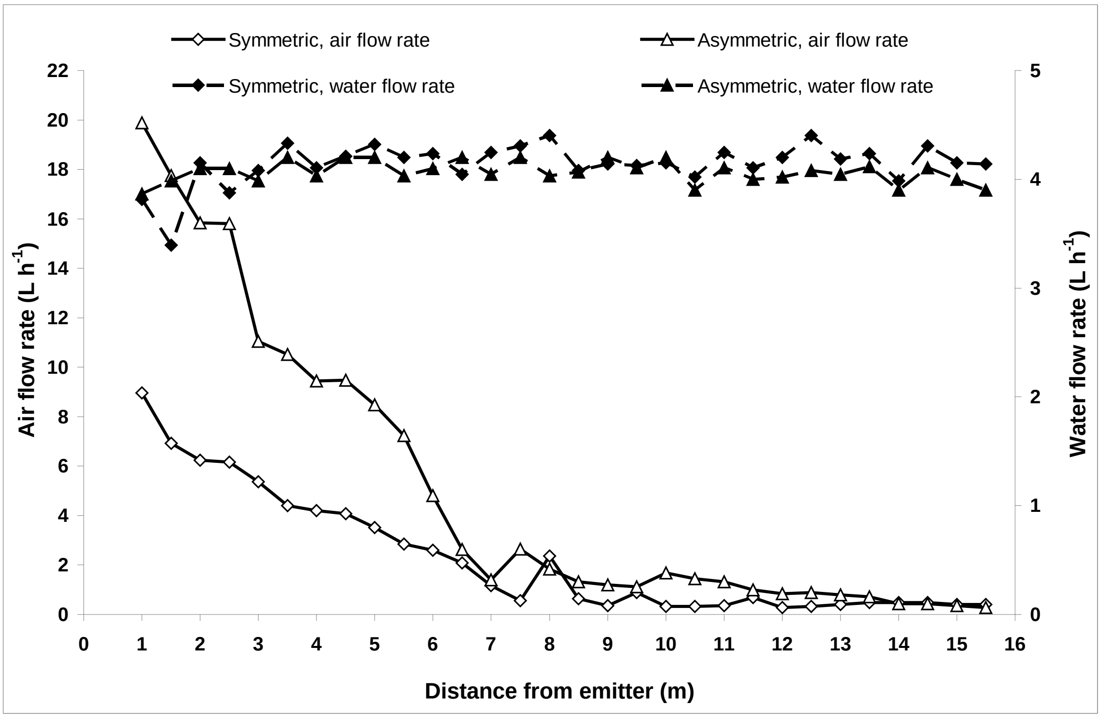

Figure 3. 21 The effect of connector geometry on the distribution of emitter air flow rates in a 19 mm ID irrigation pipe. (For asymmetric connectors, the same data for a 19 mm pipe from Figure 3.19 has been used.)

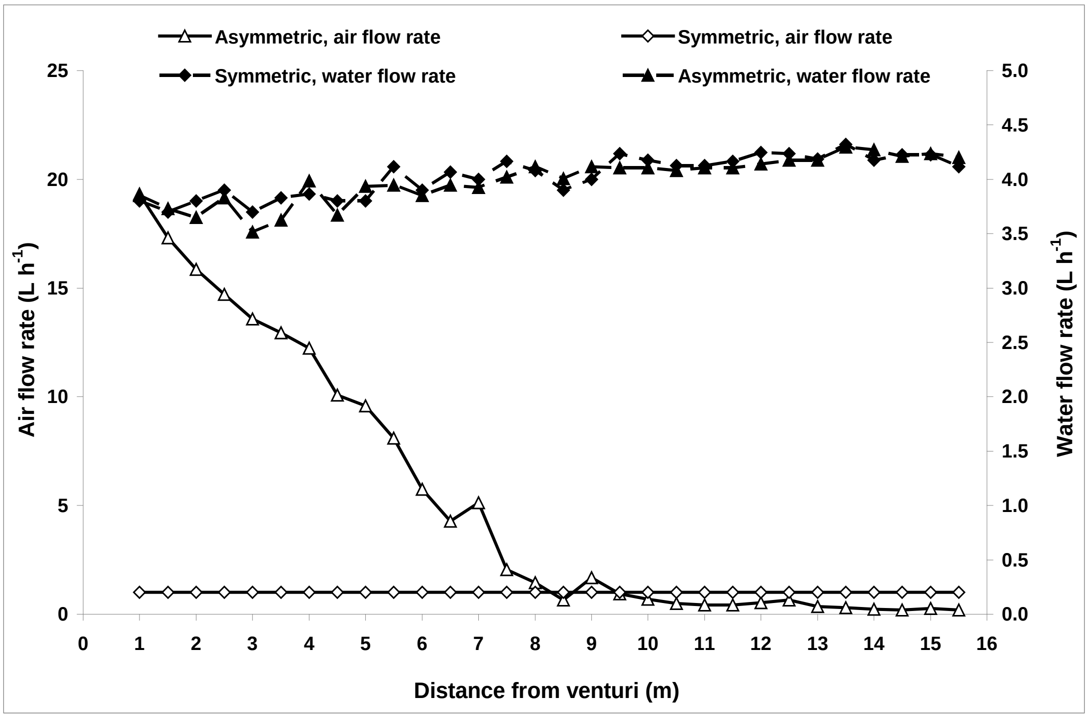

Figure 3. 22 The effect of connector geometry on the distribution of emitter air flow rates in a 25 mm ID irrigation pipe. (For asymmetric connectors, the same data for a 25 mm pipe from Figure 3.19 has been used.)

trends, a flat uniform trend with almost no air flow rate for the 25 mm ID treatment and declining trends for the 13 mm ID and 19 mm ID treatments. For the 25 mm ID treatment, it is concluded that all the air supplied by the venturi was lost from the end of the pipe. The 25 mm ID pipe with symmetric connectors had the greatest CUC but the smallest mean air flow rate and AE (Table 3.3). Air flow rates for the 13 mm ID and 19 mm ID treatments showed similar trends, however the mean air flow rate for the 13 mm ID was greater than that for the 19 mm ID treatment. Moreover, the 13 mm ID treatment showed a poorer uniformity for air flow rate distribution in comparison with the 19 mm ID treatment.

In contrast to symmetric connectors, air flow rates from all the pipe diameters showed a similar declining trend. Definitely, the similarity in the trend of the air flow rates for all the pipe diameters is attributed to the geometry of the connectors in these trials. Furthermore, data from Table 3.3 indicate an inverse relationship between pipe diameter and the CUC of air flow rates, but a direct relationship exists between pipe diameter and AE as well as the mean air flow rate.

The effect of the geometry of connectors on the distribution of air flow rates from different pipe diameters are presented in Figures 3.20-3.22. In all these Figures, air flow rates from emitters with asymmetric connectors were greater than those with symmetric ones. Moreover, as the pipe diameter with symmetric connectors increased, the slope of the emitter air flow rates decreased.

3.3.2 The effect of different concentrations of surfactant on the uniformity of air flow rates from emitters

The effect of injection of surfactant at different final concentrations consisting 0, 0.3, 0.5, 0.7, 1.0, and 1.2 ppm on the emitter air flow rates are shown in Figures 3.23 and 3.24. An increase in the surfactant concentration was associated

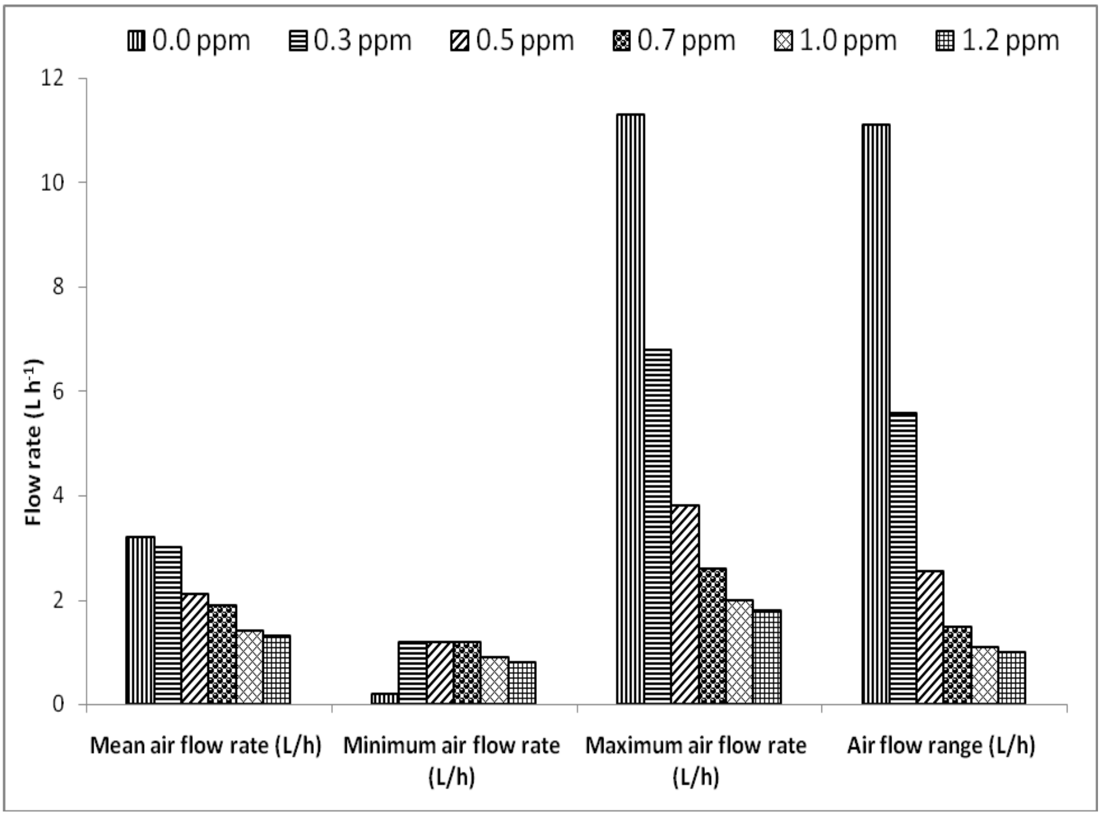

Figure 3. 23 The effect of different surfactant concentrations on the mean, minimum, maximum, and the range of emitter air flow rates (Trial 2, section 3.2.1.2).

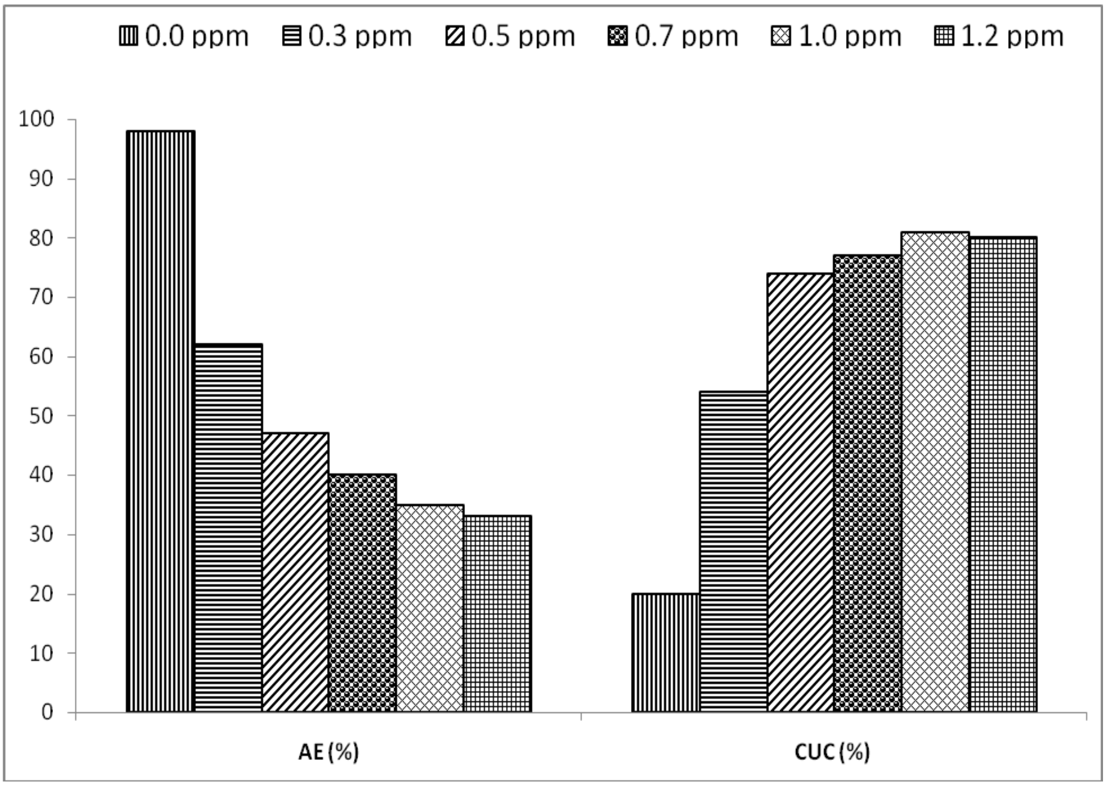

Figure 3. 24 The effect of different surfactant concentrations on the AE of the irrigation system and CUC of the emitter air flow rates (Trial 2, section 3.2.1.2).

with a decrease in the mean air flow rate, maximum air flow rate, the range of air flow rates (i.e. the difference between the maximum and minimum emitter air flow rates), and the associated AE. However, a direct relationship was observed between the surfactant concentration and the CUC. There was no consistent relationship between the surfactant concentration and the minimum air flow rate.

3.3.3 Preferential path for air flow (Trial 3)

For the layout designated as type A (Figure 3.5), air flow was observed in both laterals. The measured flow rates in the left and the right laterals were 0.479 and 0.440 L h^{-1}, respectively.

For the type B layout (Figure 3.6), air flow was observed solely in the two middle laterals. The average air flow rate for the left and the right laterals was 0.458 and 0.262 L h^{-1}, respectively. No air flow was observed in the laterals connected to the far sides of the manifold.

For the layout named type C (Figure 3.7), air flow was observed neither in the left nor in the right lateral. Air flow was observed only in the middle lateral pipe. Average air flow rate in the middle lateral was 2.016 L h^{-1}.

For the type D layout (Figure 3.8), air flow was observed only in the lateral immediately next to the junction point of the main pipe and the manifold. The average air flow rate in the lateral was 2.501 L h^{-1}. No air flow was observed in the other laterals.

3.3.4 Air and water flow rate distributions from pressure compensated on-line pot drippers with long asymmetric connectors (Trial 4)

3.3.4.1 Air and water flow rate distributions in the absence of goof plugs, with or without surfactant

Water flow rate distributions for the treatments with water alone, water and air, and water with air and surfactant are presented in Figure 3.25. Quite evidently, the treatment with water and air reduced water flow rate from emitters close to the venturi, but by 14 m distance the effect was not apparent.

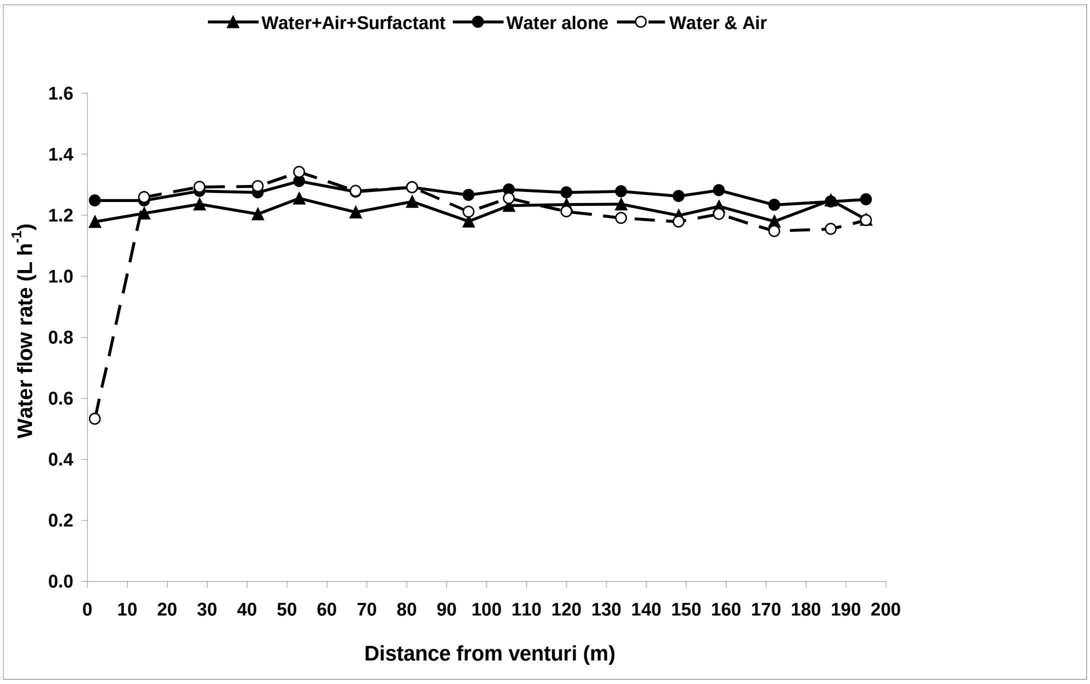

Figure 3. 25 Water flow rates in the absence of goof plugs for water, water and air, and water with air and surfactant (C_f = 32 ppm) measured from pressure compensated pot drippers with asymmetric connectors in a dead-end irrigation system.

Data on the average water flow rates and air flow rates is presented in Table 3.4 and 3.5, respectively. More details on the delivery of air bubbles (in the absence of surfactant) through the initial section of the irrigation pipe are shown in Figure 3.26. Air delivery from emitters with asymmetric connectors and in the absence of surfactant abruptly decreased just a few metres away from the venturi and eventually halted by some 8 metres from the venturi (Figure 3.26). Hence, the effective range of air delivery for the aforementioned conditions is approximately 8 meters measured from the venturi. The reduction of water flow rate from emitters close to the venturi

Table 3. 4 Water flow rate and the respective CUC for the trials in a dead-end irrigation system.

Trial number (section)	Emitter/connector Type	Without goof plugs						With goof plugs					
		Water alone (L h^{-1})	CUC (%)	Water + Air (L h^{-1})	CUC (%)	Water + Air + Surfactant (L h^{-1})	CUC (%)	Water alone (L h^{-1})	CUC (%)	Water + Air (L h^{-1})	CUC (%)	Water + Air + Surfactant (L h^{-1})	CUC (%)
4 (3.2.2.1)	Pressure compensated/ asymmetric	1.27	99	1.19	92	1.22	98	1.25	97	1.23	96	1.23	97
5 (3.2.2.2)	Pressure compensated/ symmetric	1.24	98	1.24	98	1.21	98	1.25	96	1.25	95	1.22	96
6 (3.2.2.3)	Non-pressure compensated/ symmetric	1.34	92	1.32	93	1.26	93	-	-	-	-	-	-
7 (3.2.2.4)	Non-pressure compensated drip tape	0.77	98	0.76	95	0.78	98	-	-	-	-	-	-

Table 3. 5 Air flow rate and the respective CUC for the trials in a dead-end irrigation system.

Trial number (section)	Emitter/connector Type	Without goof plugs				With goof plugs			
		Water + Air (L h^{-1})	CUC (%)	Water + Air + Surfactant (L h^{-1})	CUC (%)	Water + Air (L h^{-1})	CUC (%)	Water + Air + Surfactant (L h^{-1})	CUC (%)
4 (3.2.2.1)	Pressure compensated/ asymmetric	0.933	-82	0.226	37	0.523	-64	0.174	48
5 (3.2.2.2)	Pressure compensated/ symmetric	0.169	1	0.229	23	0.036	18	0.161	53
6 (3.2.2.3)	Non-pressure compensated/ symmetric	28*	-37	15*	42	-	-	-	-
7 (3.2.2.4)	Non-pressure compensated drip tape	135*	-85	23*	-7	-	-	-	-

*Aeration rate expressed in %.

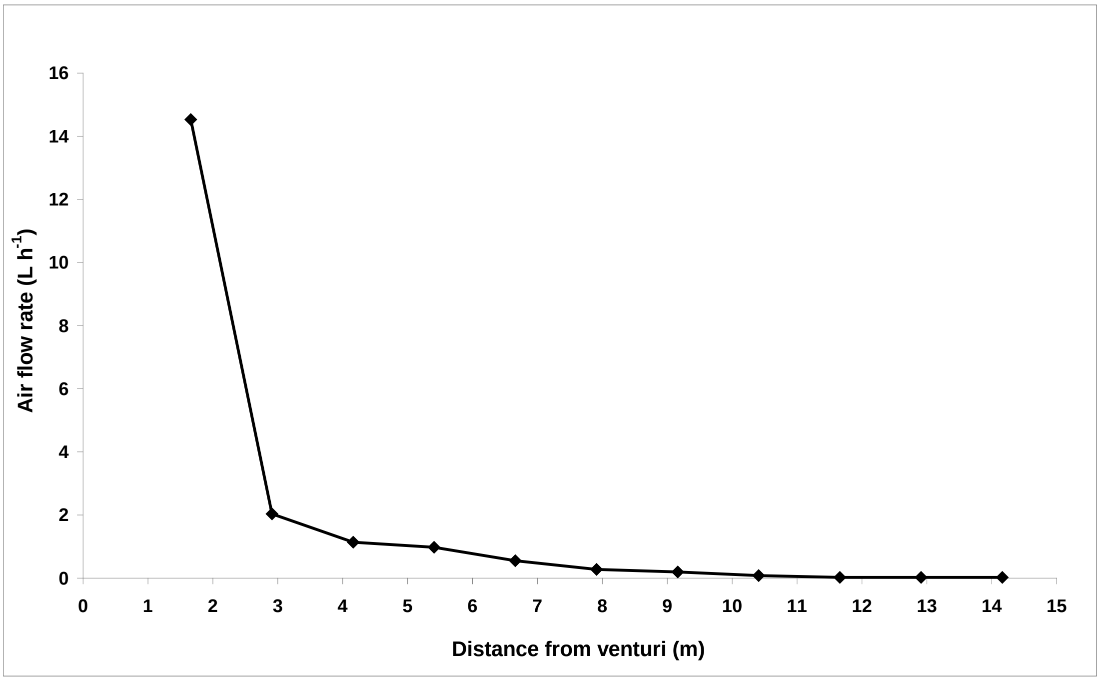

Figure 3. 26 Detailed data on emitter air flow rates from pressure compensated pot drippers with asymmetric connectors in a dead-end irrigation system, without goof plugs and surfactant.

in the first 8 m of the lateral contributes towards reducing the water distribution uniformity for the condition where air and water was flowing in the line (Table 3.4). Also, the 8 m range is true for the trials mentioned in section 3.2.1.1 (i.e. the recirculating irrigation system with asymmetric connectors) and could be seen in Figure 3.19. Distribution of emitter air flow rates without and with surfactant is presented in Figures 3.27 and 3.28, respectively.

3.3.4.2 Air and water flow rate distributions for long asymmetric connectors in the presence of goof plugs, with or without surfactant

Flow rate distributions for water alone, water and air, and water with air and surfactant are presented in Figure 3.29. As in Figure 3.25, Figure 3.29 shows an abrupt drop of water flow rate at the first sampling location which is due to displacement of water by the extraordinary high air flow rates from the proximal emitters. The average water flow rates discharged from the sampled emitters for the

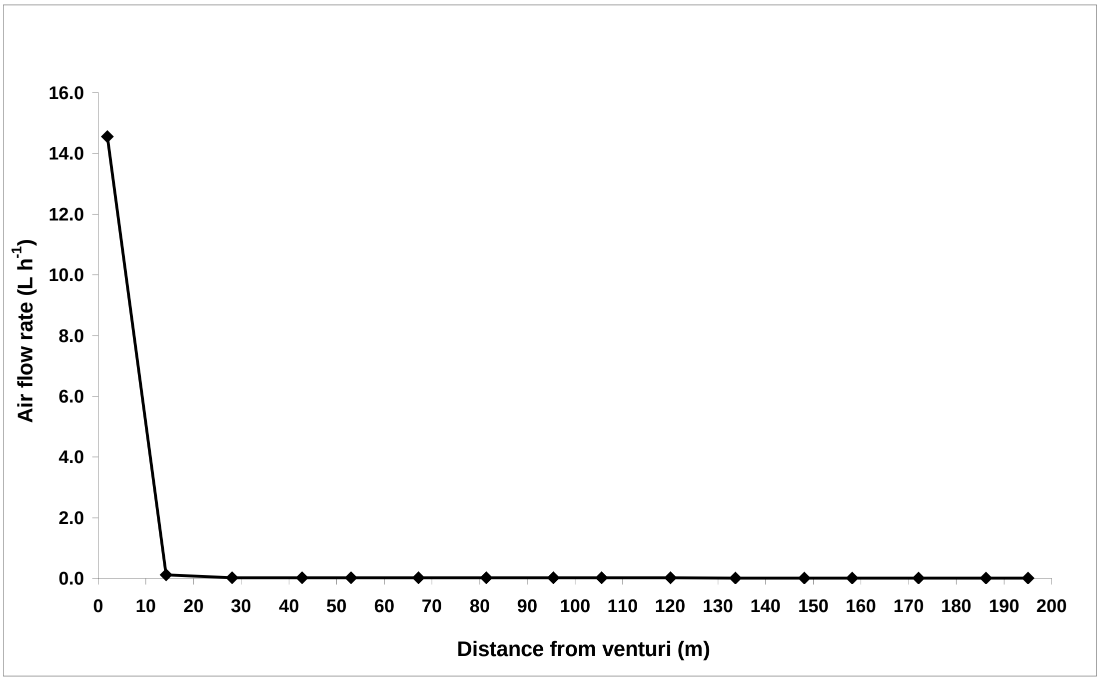

Figure 3. 27 Air flow rate in the absence of goof plugs and surfactant, from pressure compensated pot drippers with asymmetric connectors in a dead-end irrigation system.

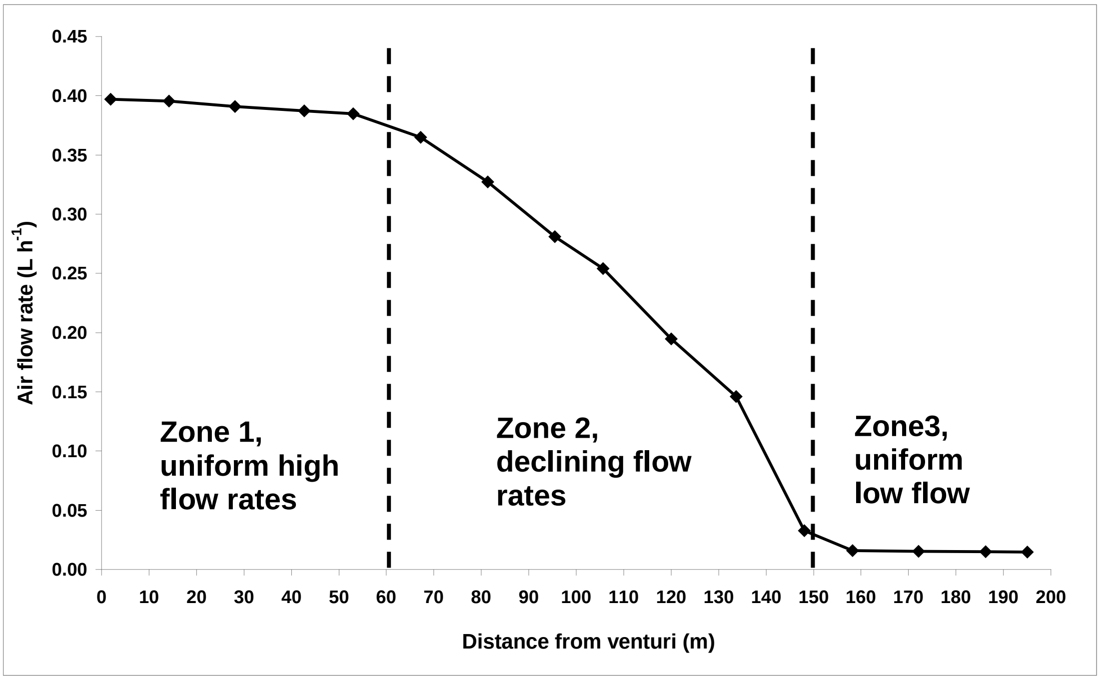

Figure 3. 28 Air flow rate in the absence of goof plugs, as affected by surfactant (C_f = 32 ppm) and measured from pressure compensated pot drippers with asymmetric connectors in a dead-end irrigation system.

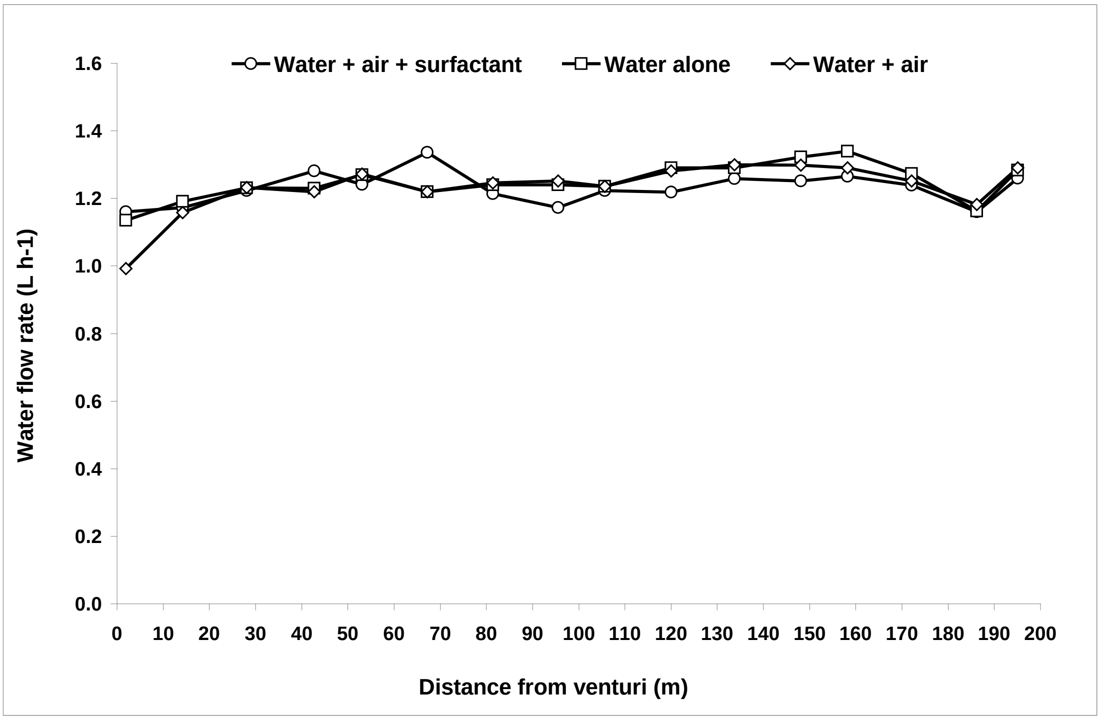

Figure 3. 29 Water flow rates in the presence of goof plugs for water, water and air, and water with air and surfactant (C_f = 32 ppm) measured from pressure compensated pot drippers with asymmetric connectors in a dead-end irrigation system.

conditions where water alone, air and water, or water with air and surfactant was flowing through the irrigation pipe are presented in Table 3.5.

Distribution of emitter air flow rates along the irrigation line without or with surfactant are shown in Figures 3.30 and 3.31, respectively. The average emitter air flow rate and the associated CUC values for this trial (No. 4) are presented in Table 3.5. Addition of surfactant to the irrigation water together with the goof plugs resulted in 175% improvement in the distribution uniformity of the air flow rates.

A comparison of the results on the distribution uniformity of air bubbles in the absence of surfactant reveals that addition of goof plugs led to 22% enhancement of the CUC. The enhancement in the uniformity of air flow rate can be seen by comparing Figure 3.27 Figure 3.30. In Figure 3.27, from the second sampling location onward, there was almost no air delivery from the emitters. However,

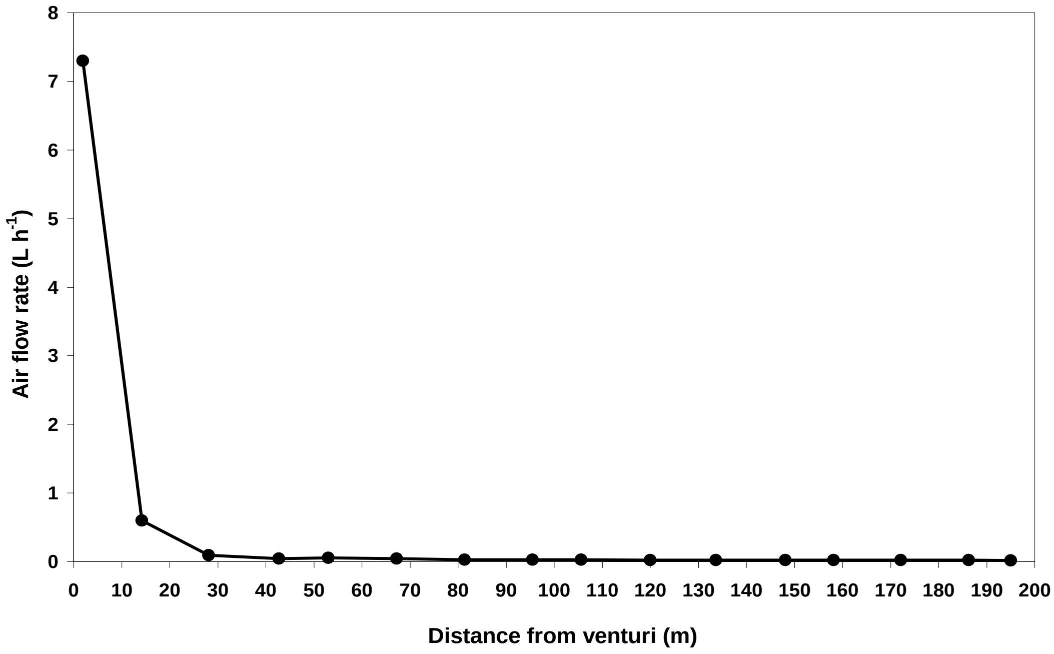

Figure 3. 30 Air flow rate in the presence of goof plugs from pressure compensated pot drippers with asymmetric connectors and no surfactant in a dead-end irrigation system.

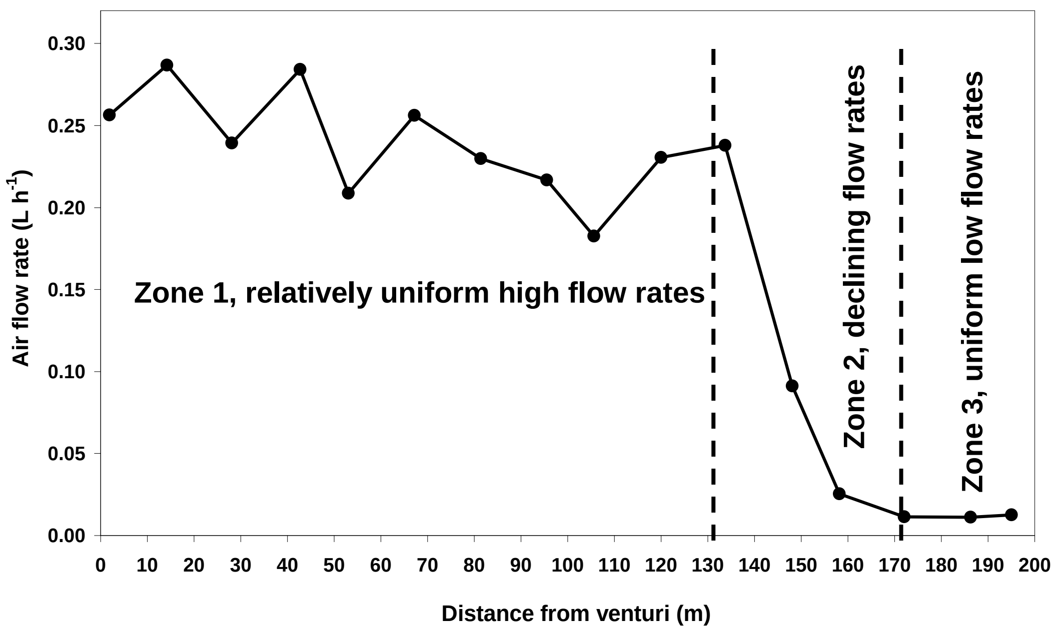

Figure 3. 31 Air flow rate as affected by surfactant (C_f = 32 ppm) and goof plugs, measured from pressure compensated pot drippers with asymmetric connectors in a dead-end irrigation system.

addition of goof plugs improved the air flow rate distribution such that in addition to the first sampling location (7.30 vs. 14.55 L h^{-1}), in the second (0.60 vs. 0.12 L h^{-1}) and a little bit in the third sampling locations (0.09 vs. 0.02 L h^{-1}) some air delivery can be seen.

For irrigation water with surfactant, addition of goof plugs resulted in 30% improvement in the CUC (Table 3.5). Although the three zones identified in Figure 3.28, are also distinguished in Figure 3.31, the range of the zones is different. Apparently, addition of the goof plugs mainly affected the range of zones 1 and 2, rather than the range of zone 3. In Figure 3.31, the range of zone 1 was extended to 134 m from the venturi (comprising 67% of the total pipe length), the beginning of zone 2 receded to a distance 130 m from the venturi and its range comprised only 20% of the total pipe length. Zone 3 receded slightly and initiated approximately 170 m from the venturi, comprising 13% of the total pipe length.

3.3.5 Air and water flow rate distributions from pressure compensated on-line pot drippers with long symmetric connectors (Trial 5)

3.3.5.1 Air and water flow rate distributions for long symmetric connectors in the absence of goof plugs, with or without surfactant

Flow rate distributions for water alone, water and air, and water with air and surfactant are presented in Figure 3.32. Average water flow rates discharged from the sampled emitters for the conditions where water only, air and water, or water with air and surfactant was flowing through the irrigation pipe are presented in Table 3.4.

Air flow rates without surfactant are shown in Figure 3.33. In contrast to the previous air flow rate distributions (asymmetric connectors without surfactant), particularly those presented in Figures 3.27 and 3.30, two main features are distinguished in Figure 3.33. First, the maximum air flow rate occurred somewhere

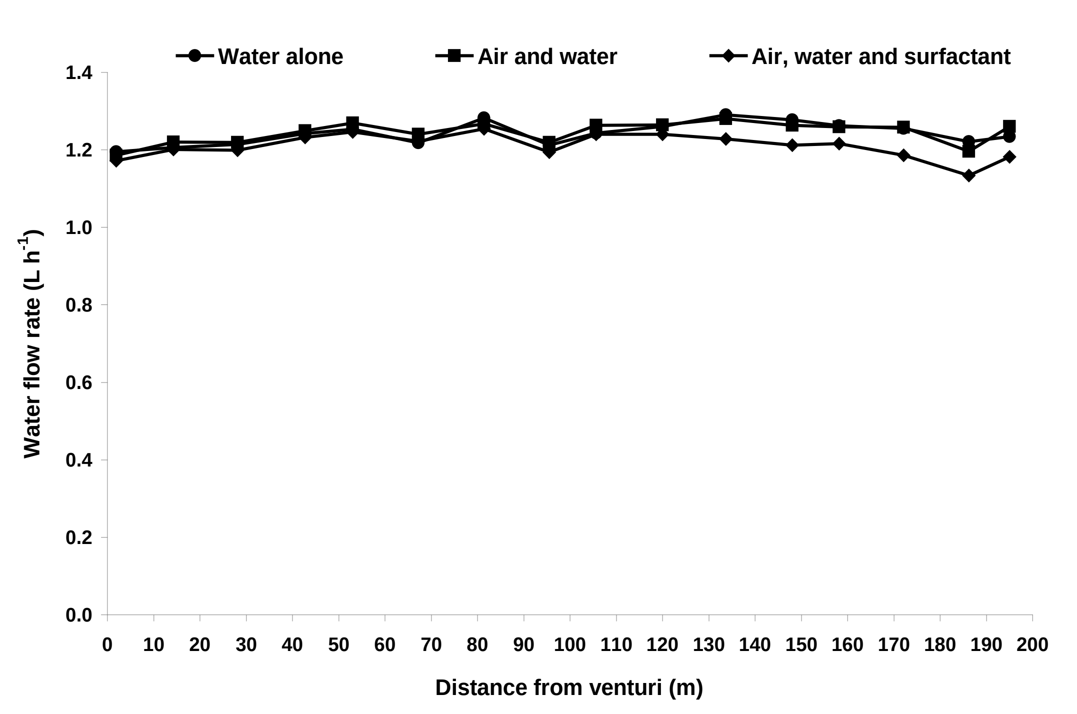

Figure 3. 32 Water flow rates in the absence of goof plugs for water, water and air, and water with air and surfactant (C_f = 32 ppm) measured from pressure compensated pot drippers with long symmetric connectors in a dead-end irrigation system.

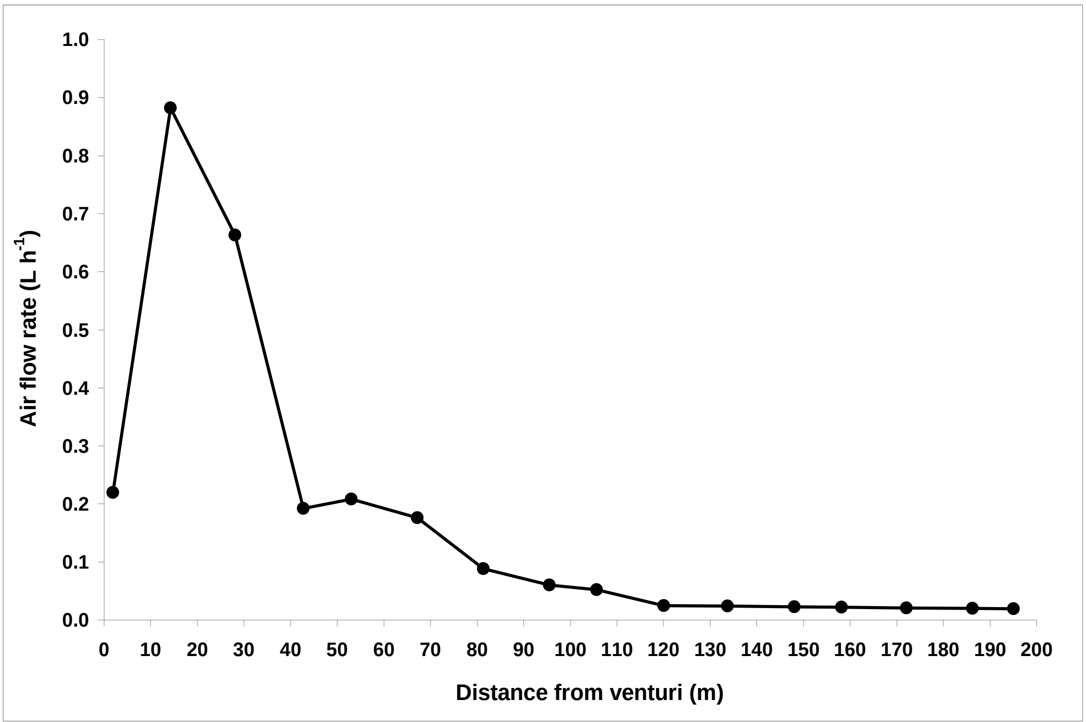

Figure 3. 33 Air flow rate in the absence of goof plugs and surfactant from pressure compensated pot drippers with long symmetric connectors in a dead-end irrigation system.

other than the first sampling location (about 14 m from the venturi, at the second sampling location). Second, the uniformity of air flow rate distribution is better than those with asymmetric connectors with (Figure 3.30) and without goof plugs (Figure 3.27).

Air flow rates with surfactant are shown in Figure 3.34. In the Figure, three zones can be recognized. Zone 1 comprises the first 30 m of the pipe corresponding to 15% of the total pipe length and is distinguished by its abrupt drop in the air flow

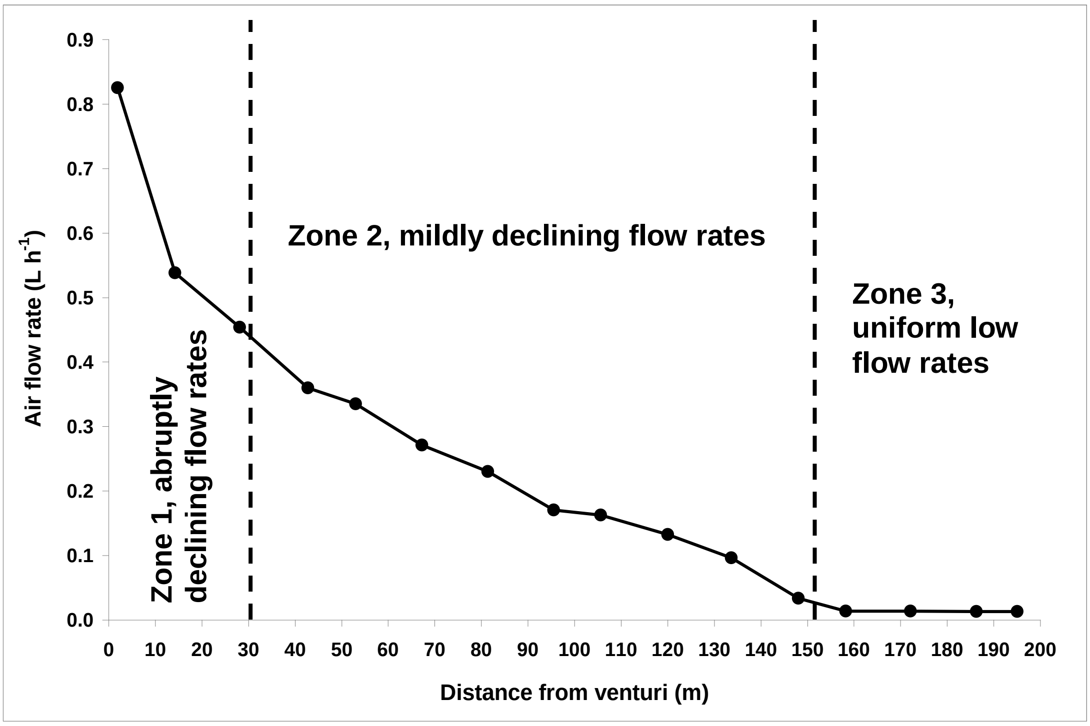

Figure 3. 34 Air flow rate in the absence of goof plugs, as affected by surfactant (C_f = 32 ppm) and measured from pressure compensated pot drippers with long symmetric connectors in a dead-end irrigation system.

rates. Zone 2 begins 30 m from the venturi and ends 150 m from the venturi comprising 62% of the irrigation pipe. It shows a relatively mild decline in the air flow rates. Zone 3 presents a uniform and horizontal trend with almost zero air flow rate, comprising 23% of the pipe length.

Addition of surfactant to the irrigation water enhanced the CUC of the emitter air flow rates by 22% (Table 3.5). Compared to the asymmetric connectors without goof plugs (Section 3.3.3.1), the CUC of air flow rates without surfactant was 101% better. However, when addition of surfactant is considered, it reveals that the CUC for the symmetric connectors was 38% worse compared to the asymmetric connectors (Table 3.5). It follows that in the absence of surfactant, symmetric connectors provide a more uniform air flow rate distribution than asymmetric connectors. However, addition of surfactant to the irrigation water enhanced the uniformity of airflow rates more for asymmetric connectors than for the symmetric ones.

3.3.5.2 Air and water flow rate distributions for long symmetric connectors in the presence of goof plugs, with or without surfactant

Flow rate distributions for water alone, water and air, and water with air and surfactant are shown in Figure 3.35. Average water flow rates discharged from the sampled emitters for the conditions where water only, air and water, or water with air and surfactant are presented in Table 3.4.

Air flow rate distribution in the absence of surfactant is shown in Figure 3.36. The most prominent feature of the Figure is its particular shape which distinguishes it from the previous graphs. In contrast to the previous graphs, the maximum air flow rate occurred somewhere in the middle of the pipe (81 m from the venturi) rather than at the very beginning of the pipe. In comparison with section 3.3.4.1 for the trial without surfactant, addition of goof plugs enhanced the CUC by 94% (Table 3.5).

Air flow rate distribution in the presence of surfactant is presented in Figure 3.37. The shape of the air flow rate distribution is similar to the one in Figure 3.31 (goof plugs and surfactant with asymmetric connectors). The presence of goof plugs

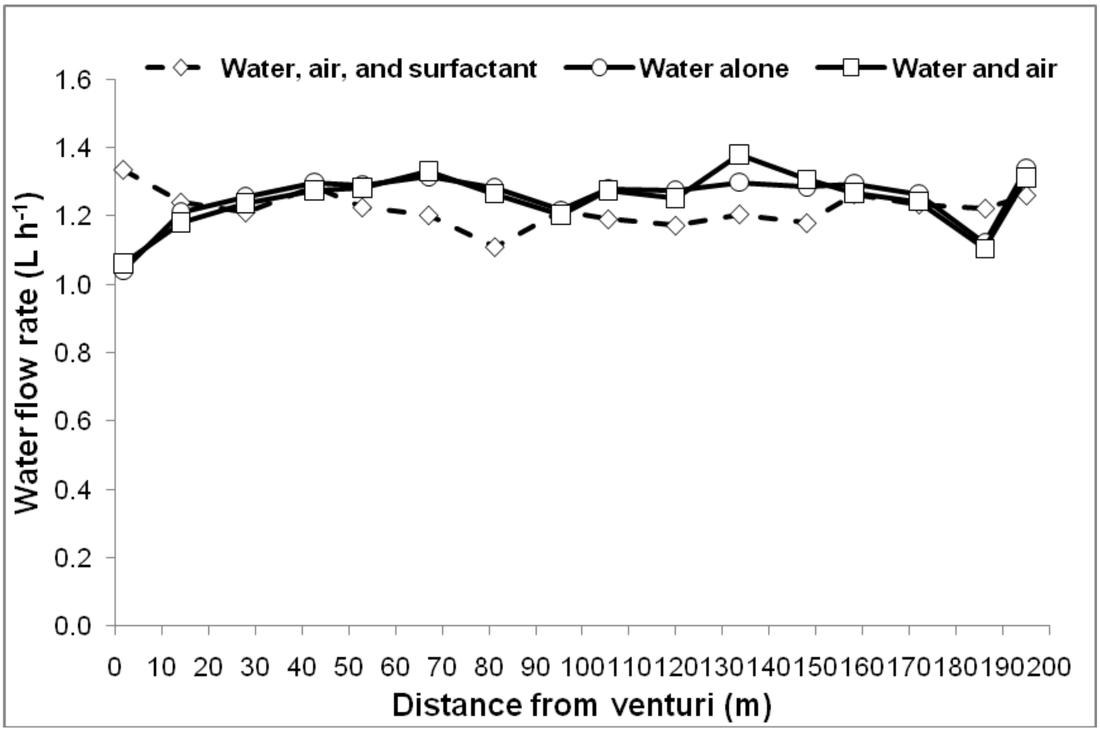

Figure 3. 35 Water flow rates in the presence of goof plugs for water, water and air, and water with air and surfactant (C_f = 32 ppm) measured from pressure compensated pot drippers with symmetric connectors in a dead-end irrigation system.

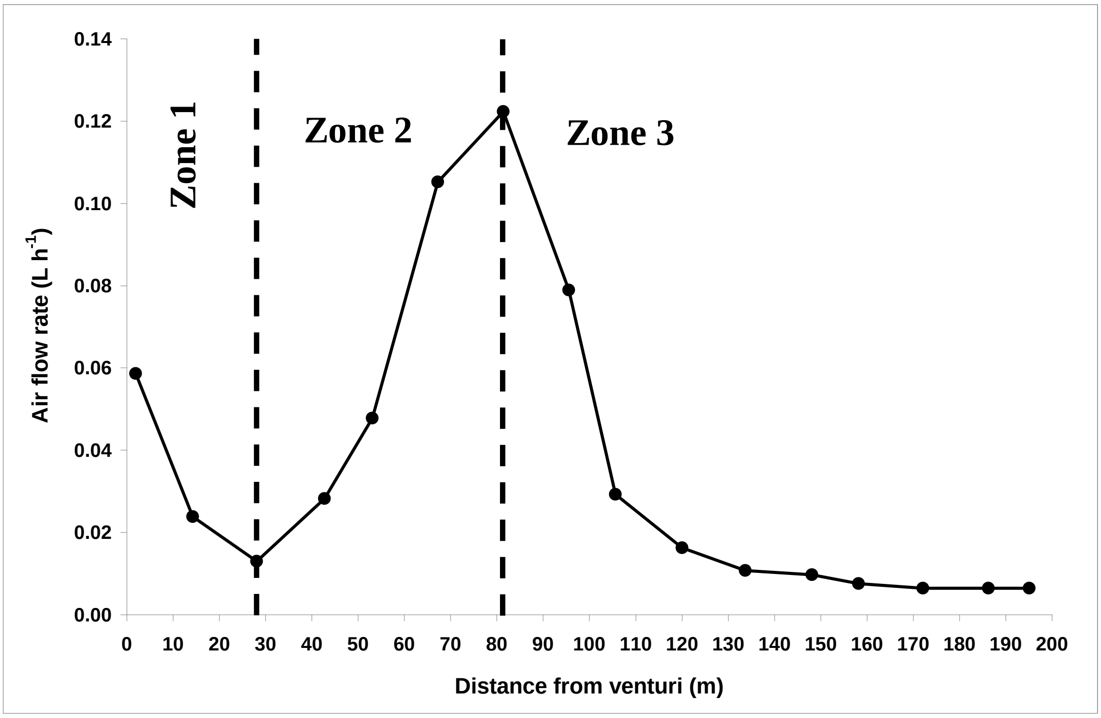

Figure 3. 36 Air flow rate in the presence of goof plugs from pressure compensated pot drippers with symmetric connectors and no surfactant in a dead-end irrigation system.

together with the addition of surfactant to the irrigation water led to a 194% enhancement in the uniformity of air flow rate distribution (Table 3.5).

A comparison between the calculated CUC in the presence of surfactant in this section with the CUC with surfactant in section 3.3.3.2 reveals that use of symmetric connectors resulted in 10% more enhancement in uniformity than did the asymmetric ones (Table 3.5).

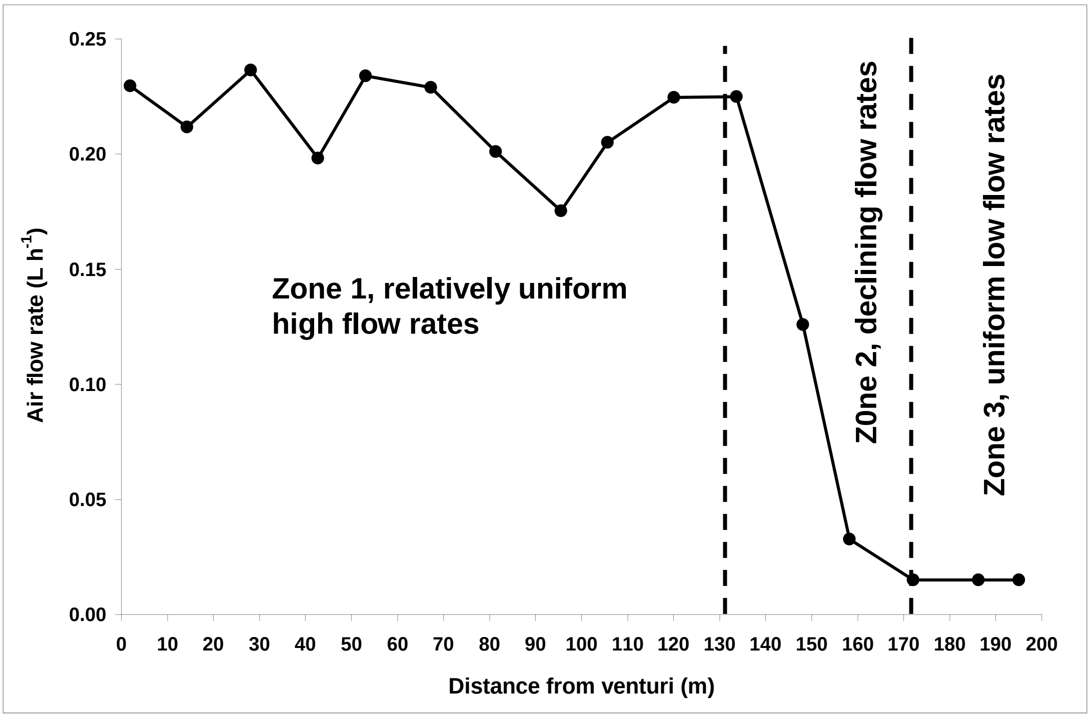

Figure 3. 37 Air flow rate in the presence of goof plugs, as affected by surfactant (C_f = 32 ppm) and measured from pressure compensated pot drippers with symmetric connectors in a dead-end irrigation system.

The combined effect of goof plugs and surfactant resulted in formation of three zones in the air flow rate distribution (Figure 3.37). The range of the zones as well as their corresponding positions are very similar to those in Figure 3.31; indicating that concurrent utilization of 32 ppm surfactant and asymmetric goof plugs inserted immediately before the connectors will cancel out the effect of the geometry of connectors on the trend of air flow distribution.

3.3.6 Air and water flow rate distributions from non-pressure compensated on-line pot drippers with short symmetric connectors (Trial 6)

Flow rate distributions for water alone, water and air, and water with air and surfactant are presented in Figure 3.38. From Figure 3.38, it is evident that the water flow rate at the first sampling location was not affected by the high aeration rate at that location. Average water flow rates discharged from the sampled emitters for the conditions where water alone, air and water, or water with air and surfactant was flowing through the irrigation pipe are presented in Table 3.4.

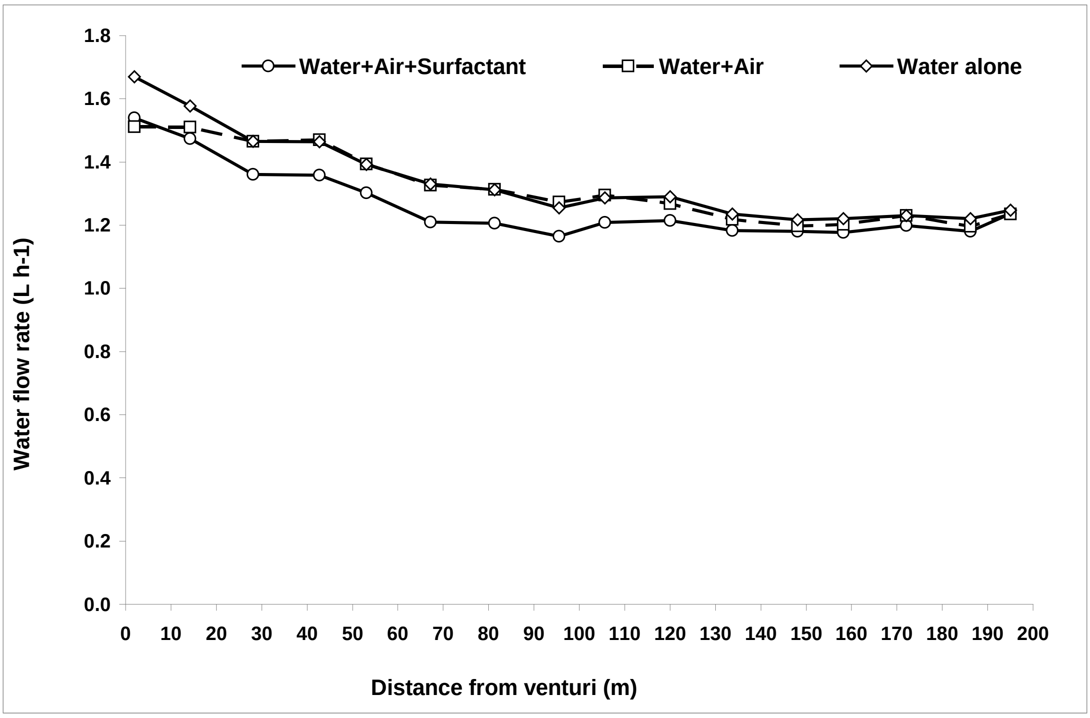

Figure 3. 38 Flow rates for water, water and air, and water with air and surfactant (C_f = 32 ppm) measured from the non-pressure compensated pot drippers with short symmetric connectors in a dead-end irrigation system.

Aeration rates without or with surfactant are shown in Figures 3.39 and 3.40, respectively. Addition of 32 ppm surfactant to irrigation water in an irrigation system with short symmetric connectors and non-pressure compensated emitters led to 214% more enhancement in the uniformity of air delivery by the emitters (Table 3.5). This shows that the greatest benefit from the addition of surfactant to the irrigation water

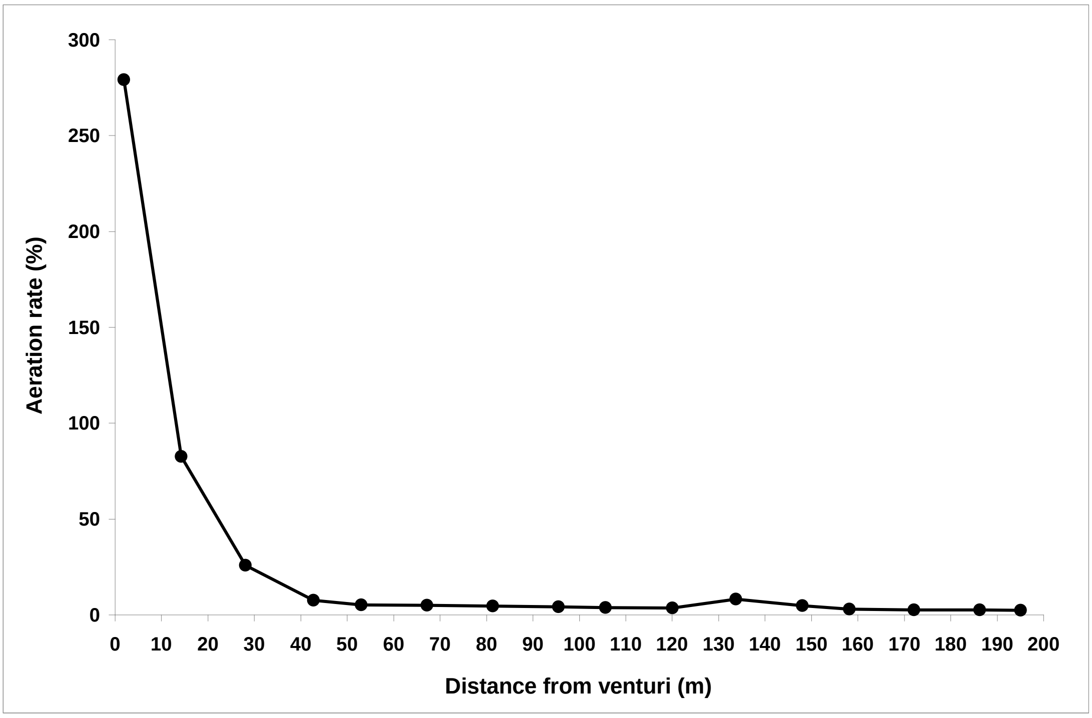

Figure 3. 39 Aeration rates from non-pressure compensated pot drippers with short symmetric connectors and no surfactant in a dead-end irrigation system.

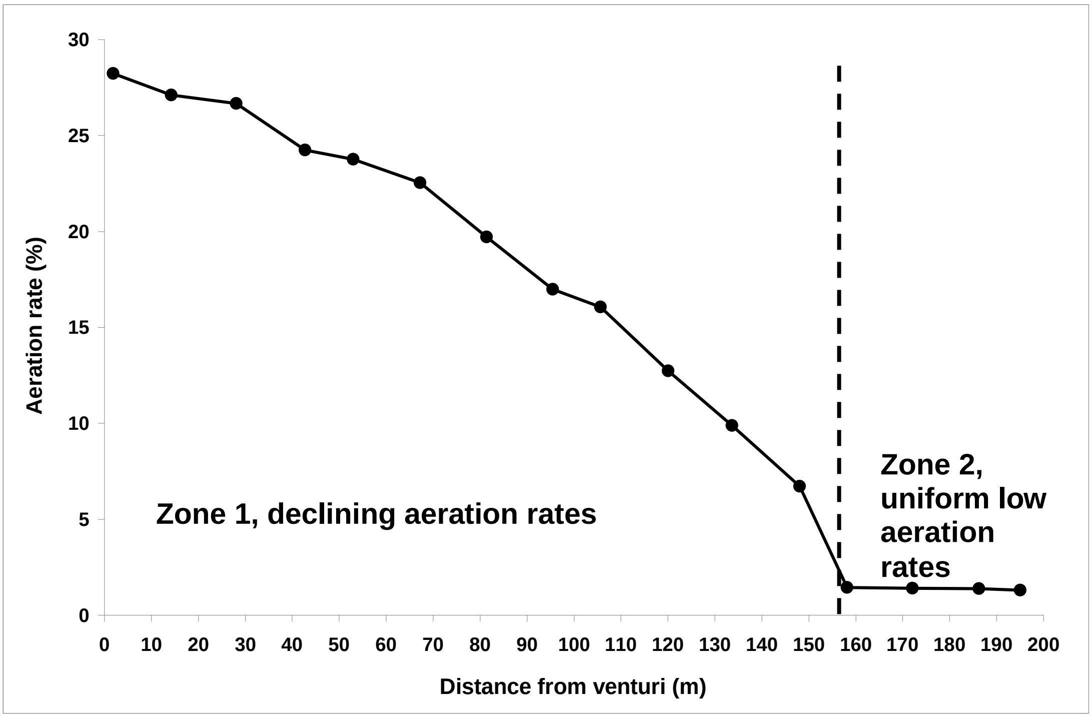

Figure 3. 40 Aeration rates as affected by surfactant (C_f = 32 ppm) and measured from non-pressure compensated pot drippers with short symmetric connectors in a dead-end irrigation system.

on the uniformity of distribution of air bubbles was obtained in the system utilizing short asymmetric connectors and non-pressure compensated emitters (Table 3.5).

In contrast to the previous trials, addition of surfactant to the irrigation water resulted in formation of only two zones along the length of irrigation pipe representing distribution of aeration rates. Zone 1, with a declining trend, comprises up to 80% of the total length of the pipe. Zone 2 shows a uniform trend of low aeration rates, comprising 20% of the pipe.

3.3.7 Air flow rate distribution from non-pressure compensated emitters on an integral dripperline (Trial 7)

Flow rate distributions for water alone, water and air, and water with air and surfactant are presented in Figure 3.41. Average water flow rates discharged from the sampled emitters for the conditions where water only, air and water, or water with air and surfactant was flowing through the dripperline are presented in Table 3.4. Figure 3.41 clearly shows the drop off in water flow rate at the first sampling location due to displacement of water by the extraordinary high aeration rate delivered through the emitters at that location.

Aeration rates without or with surfactant are shown in Figures 3.42 and 3.43, respectively. Average aeration rates without or with surfactant were 135% and 23%, respectively, and the calculated CUC values for the foregoing conditions were -85% and -7%, respectively (Table 3.5). A negative CUC indicates very poor uniformity. The non-uniformity in the distribution of air flow rates was so poor that even addition of surfactant to the irrigation water did not yield a positive value for the resulting CUC. Two zones are distinguishable in Figure 3.43, but in contrast to Figure 3.40, zone 1 is short and terminated by an abruptly declining trend; it comprised only 13% of the total pipe length. Zone 2 shows a mild decline in the

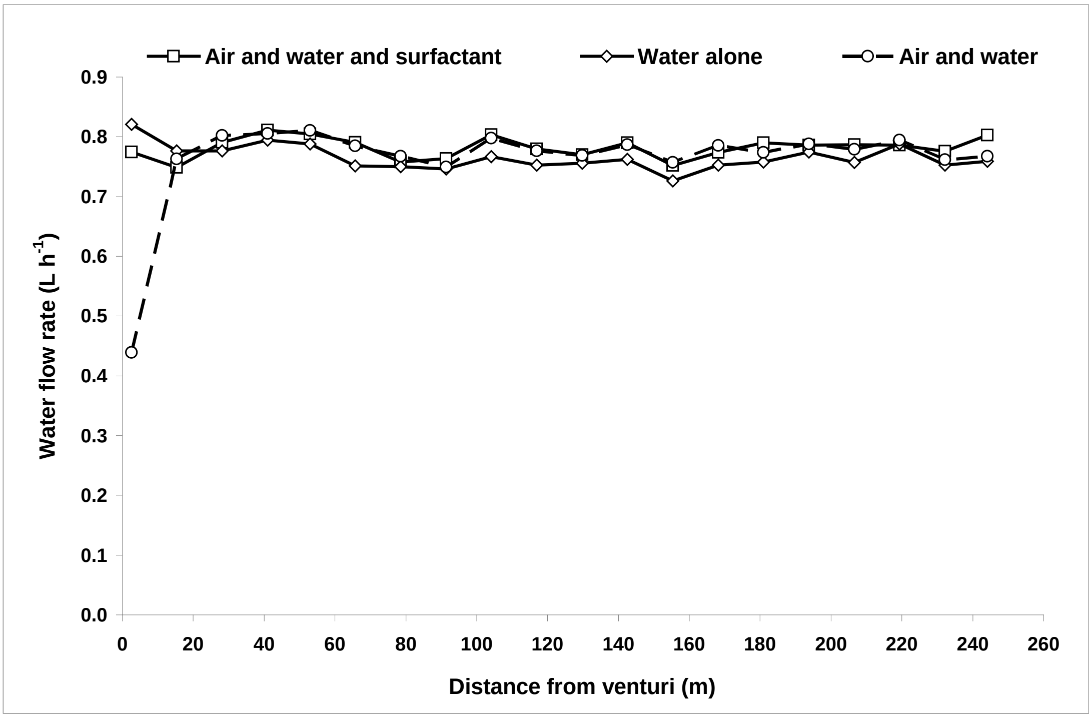

Figure 3. 41 Flow rates for water, water and air, and water with air and surfactant (C_f = 62 ppm) measured from the non-pressure compensated integral drippers on a dipperline in a dead-end irrigation system.

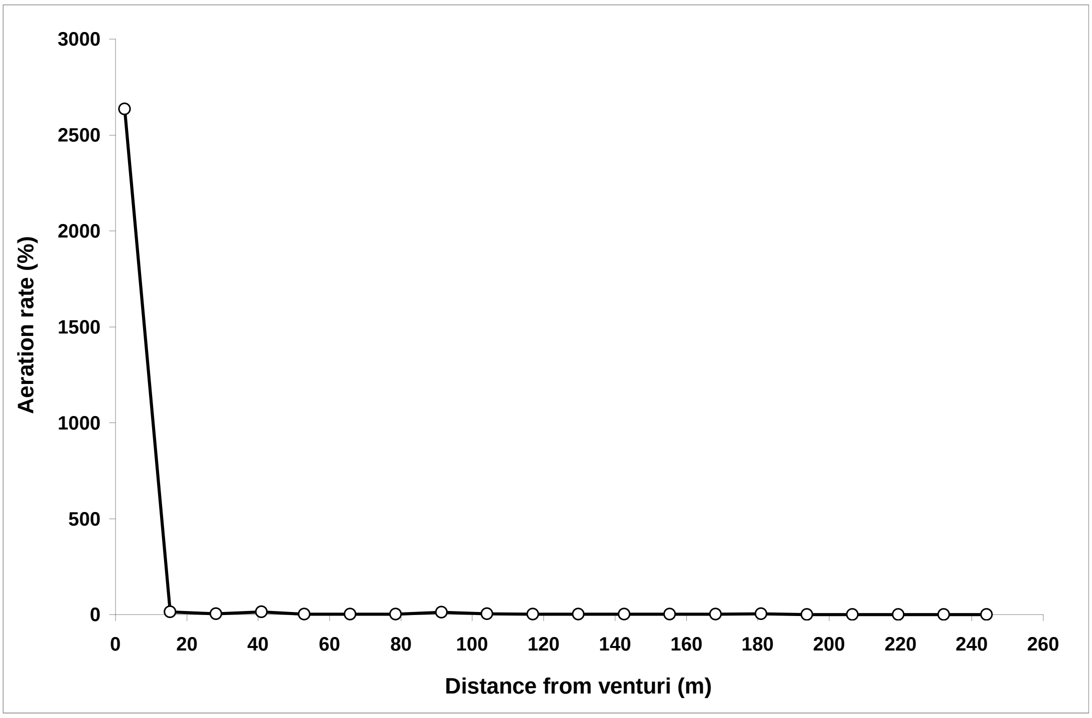

Figure 3. 42 Aeration rates from non-pressure compensated integral drippers on a dripperline and no surfactant in a dead-end irrigation system.

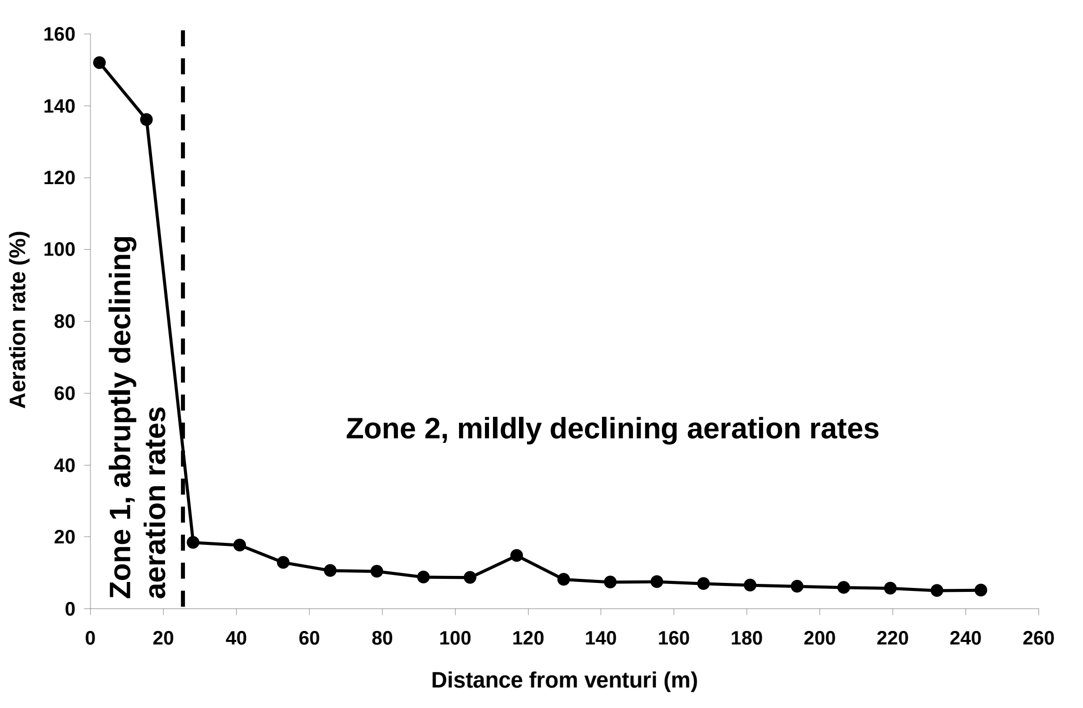

Figure 3. 43 Aeration rates as affected by surfactant (C_f = 62 ppm) and measured from non-pressure compensated integral drippers on a dripperline in a dead-end irrigation system.

trend of the aeration rate over the remaining 87% of the pipe length.

3.4 Discussion

3.4.1 The effect of CSA, pipe diameter, and geometry of connectors on the uniformity of water and air flow rates from emitters (Trial 1)

3.4.1.1 As affected by emitter CSA

Both emitter types showed a linear distribution trend in water flow rates as can be seen from Figure 3.17. However, water flow rates from the first few emitters were less than their corresponding nominal water flow rates (i.e. 1.2 L h^{-1} for the small CSA emitters and 4.0 L h^{-1} for the large CSA ones) which was due to the displacement of water by the relatively high air flow rates at the beginning of the pipe.

In contrast to the water flow rates, the distribution of air flow rates from both irrigation pipe. This reveals that in these emitters, the orifice of an emitter is pressure compensable only to water rather than air. Moreover, the result of paired t-test for the air flow rate data showed a significant difference at 5% level of confidence for air flow delivery between these two types of emitters. It is noteworthy that 140% relative reduction in the CSA of the emitters led to a huge relative reduction in the water flow rate of the emitters (i.e. $\left(\frac{4.1-1.2}{1.2}\right)\times 100 = 242\%$) whereas the relative reduction in the mean air flow rates was markedly small (i.e. $\left(\frac{5.1-3.2}{3.2}\right)\times 100 = 59\%$). This is explained by the extraordinarily large difference in the compressibility of air in comparison to that of water. At a given temperature, e.g. 15.5 °C, the compressibility of air is approximately 15000 times greater than that of water (Graebel 2001). It is concluded that based on the findings of this experiment, for an irrigation system similar to the one described in section 3.2.1 for 19 mm ID pipe with asymmetric connectors and 30 emitters spaced at 50 cm each of average water flow rate of 4.1 L h^{-1}, 123 L water and 153 L of air could be discharged after 60 minutes of irrigation. To deliver the same water volume but with 1.2 L h^{-1} emitters, the irrigation system must run for 205 minute and is estimated to deliver 328 L air. It follows that the efficacy of root zone aeration, particularly for plants grown on fine textured soils, might be improved by using very low flow rate emitters (e.g. less than 0.5 L h^{-1}) without marked reduction in the emitter air flow rates over distance.

A close examination of Figure 3.17 reveals that from the beginning of the pipe down to the point 6.5 m away from the venturi (i.e. 38% of the total pipe length), the large CSA emitters delivered markedly higher air flow rates than did the small CSA ones. Notwithstanding, the discrepancy in airflow rates over the first 38% of the pipe narrowed so that from the point 6.5 m downward to the last emitter (i.e. 62% of the total pipe length) there was almost no difference in air flow rates between the corresponding emitters.

The calculated efficiency of air bubble delivery for both treatments suggests that 98 % of the air volume supplied by the venturi was delivered within a short distance of 17 m from the venturi, and the remainder left the irrigation pipe unused (i.e. was not discharged through the emitters). However, the very low CUCs, particularly the one calculated for the large CSA, indicates very non-uniform distributions of air flow rates along the irrigation pipe.

3.4.1.2 Air flow rate as affected by pipe diameter with symmetric connectors

From Table 3.3, the mean water flow rates measured from the different pipe diameters were close to the nominal emitter flow rate and hence were not affected by the pipe diameter.

In contrast to water flow rate, mean air flow rates as well as aeration efficiencies were inversely affected by the pipe diameter. The larger the pipe diameter, the smaller the magnitude of the calculated mean air flow rates and aeration efficiencies. This is explained as follows. For a given time interval and pressure differential across a venturi, a certain volume of air will be drawn into the irrigation pipe. As the air enters into the pipe, it forms in bubbles at the upper surface of the horizontal pipe (Sankey et al. 2009) (Figure 3.44). As long as the depth of the region where air bubbles are flowing, is greater than the protruded length of the connector (Figure 3.45), air bubbles can be available to the emitter. The larger the depth of submerged length of the connector (SLC), the more air bubbles are likely to

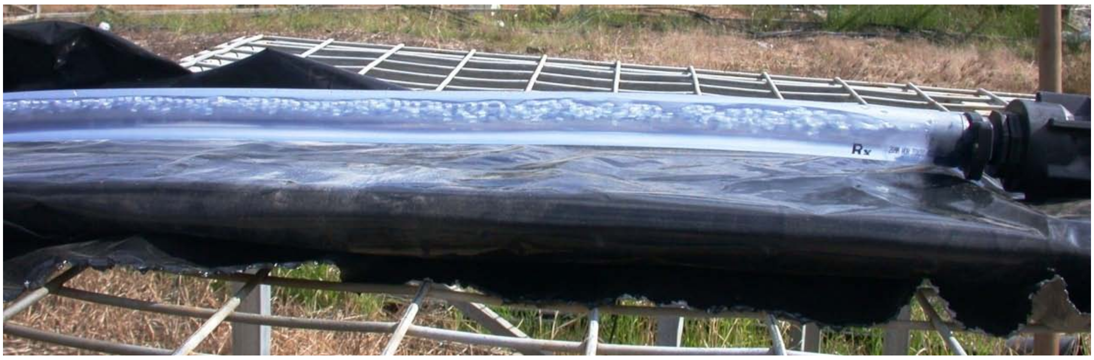

Figure 3. 44 Formation of air bubbles in an irrigation pipe immediately after a venturi.

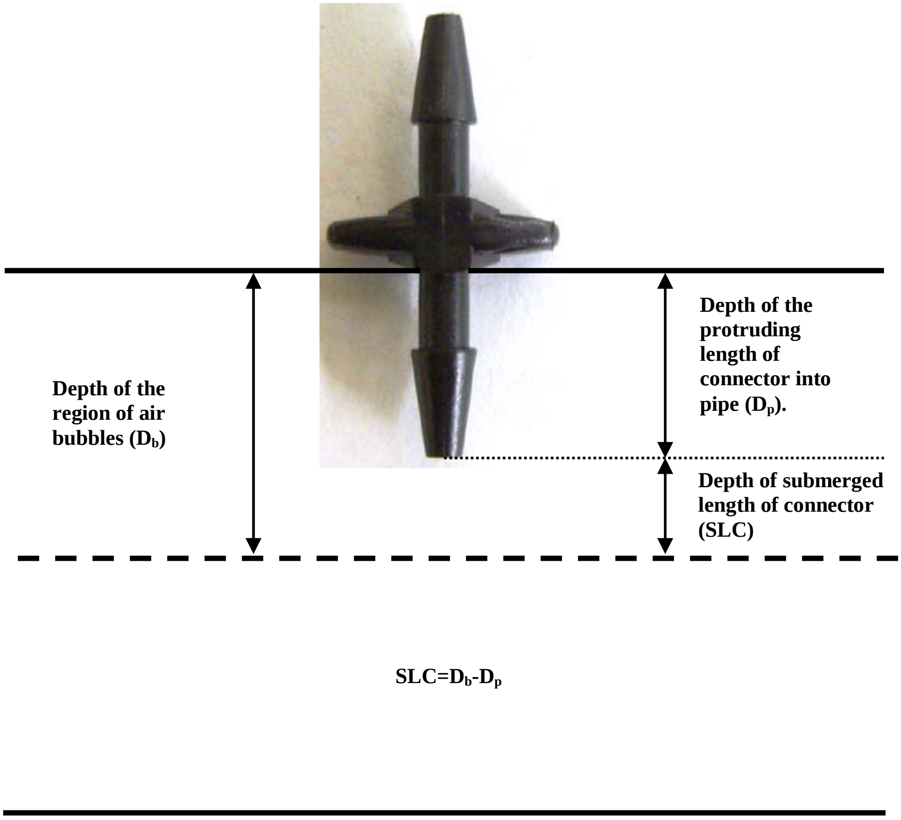

Figure 3. 45 Factors influencing delivery of air bubbles to emitter via a symmetric connector. Air bubbles are deliverable to emitter only if the submerged length of connector (SLC) is greater than 0.

be drawn into the connector. Moreover, the larger the pipe diameter, the smaller the depth of the region occupied by the air bubbles. In the trials where symmetric connectors were used, this principle was responsible for the availability of the air bubbles to emitters. Figure 3.46 shows a symmetric connector where the protruded

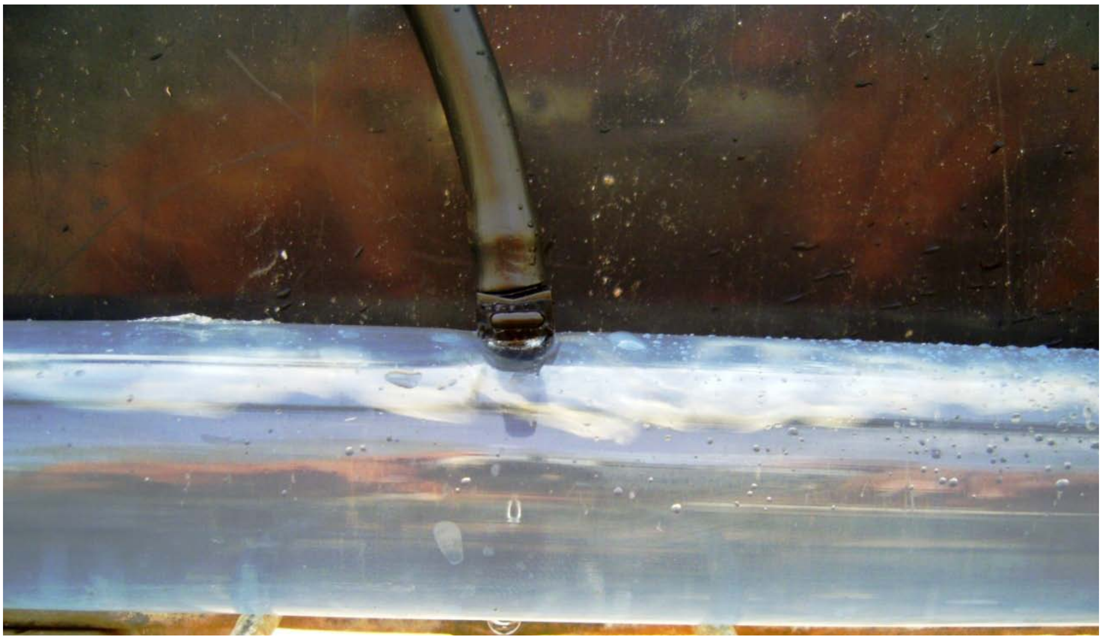

Figure 3. 46 A symmetric connector with protruded length larger than the depth of the region of air bubbles (SLC<0).

length is longer than the depth of the region occupied by air bubbles. Since SLC<0, only water can be drawn into the connector and hence the emitter receives no air via that connector. From Table 3.3, it can be seen that for a given pipe diameter and symmetric connectors, the less air bubbles were available to the emitters, the more air bubbles were left the irrigation system via the return flow leading to a poorer efficiency of air bubble delivery. In other words, for symmetric connectors, as the pipe diameter increased, the depth of the region occupied by air bubbles was smaller compared to efficiency of air bubble delivery. In other words, for symmetric connectors, as the pipe diameter increased, the depth of the region occupied by air bubbles was smaller compared to the protruded length of connector. This resulted in less air available for release through emitters and consequently a decrease in the mean air flow rate along the pipe.

From Table 3.3 (regardless of the connector type), it can be seen that an increase in the mean air flow rate was always followed by a decrease in CUC. As mentioned in the previous sub-section, the emitters are originally designed and manufactured to regulate only the flow of water (an almost incompressible fluid) rather than air (an extremely compressible fluid) against a given range of variations in the water pressure. In other words, emitters appear to behave like fully open conduits when air bubbles are available for discharge. Hence, for the limited supply of air volume into the pipe, the relatively higher delivery of air flow through the proximal emitters not only led to higher mean emitter air flow rate but also resulted in the availability of less air bubbles for the distal emitters and a poorer uniformity of air flow rate along the pipe. The inverse relationship between the mean air flow rate and CUC was observed in all trials as shown in sections 3.3.1-3.3.7.

3.4.1.3 *Air flow rate as affected by pipe diameter with asymmetric connectors*

As is shown in Table 3.3, an increase in the pipe diameter resulted in a decrease in CUC but an increase in both the mean air flow rate and the efficiency of air bubble delivery. This is explained as follows. For a given pipe diameter with asymmetric connectors, the availability of air bubbles to the emitters depends on two variables: the submerged length of connector (the general principle described in sub-section 3.4.1.2), and the local suction force resulted from pressure drag around the opening of the connector. As water moves past an object, its pressure is changed. At the upstream face of the object, water flow comes to a stop; therefore a high pressure region is created ahead of the object. The water moving around the sides and downstream face of the object creates a low pressure region behind the object (Denny 1993). Generally, an object with a very wide or abrupt change in the contours of its shape from front to back (such as an asymmetric connector, Fig. 3.2) creates a greater pressure differential compared to an object with a geometrically regular shape (such as a symmetric connector, Fig. 3.3). The reason is that the streamlines are not able to exactly follow the abrupt changes in the contours, leading the boundary layers to separate and result in formation of a low pressure region and turbulent flow behind the object (Fig. 3.47) (McLester & St. Pierre 2008). The

Figure 3. 47 The turbulent flow at the vicinity of an asymmetric connector.

pressure differential between the upstream and downstream faces of an asymmetric connector causes a suction force around the opening of the connector which enhances the availability of air bubbles to this type of connector. Drag force is proportional to the second power of water velocity (Johnson 1998). It follows that a small change in the water velocity will cause a great change in the resulting drag force. The inverse relationship between the average emitter air flow rate and pipe diameter with asymmetric connectors can be explained by the effect of velocity on the resulting drag force. In all the trials concerning the effect of pipe diameter on the average emitter air flow rate, the pressure at the inlet and outlet of the venturi and the return to the water tank was maintained at 345 kPa (50 psi), 103 kPa (15 psi), and 69 kPa (10 psi), respectively. The motive flow rate and average water velocity for the 13 mm pipe diameter were 0.042 L s^{-1} and 0.316 m s^{-1}, respectively. Clearly, for a larger pipe diameter a larger motive flow rate is required to maintain the foregoing pressure conditions. For the 25 mm pipe diameter, the motive flow rate and average water velocity was 0.380 L s^{-1} and 0.774 m s^{-1}, respectively. The larger water velocity in the 25 mm pipe diameter in comparison with that in the 13 mm pipe diameter indicates formation of a larger drag force on the asymmetric connectors of the larger pipe diameter resulting in a stronger local turbulence.

In contrast to the symmetric connectors, the turbulent flow around the asymmetric connectors leads to increased availability of air bubbles not only to the proximal emitters, but also to the distal ones where the depth of the region occupied by air bubbles is smaller than the protruded length of the connector. In recirculating irrigation systems, the capability of the asymmetric connectors in delivery of air bubbles to the distal emitters explains the higher efficiency of air bubble delivery associated with this type of connector in comparison with the symmetric ones.

3.4.2 The effect of different concentrations of surfactant on the uniformity of air flow rates from emitters (Trial 2)

The direct relationship between surfactant concentration and maximum air flow rate, mean air flow rate, range of air flow rates, and CUC is explained by the effect of surfactant on water surface tension.

The pressure differential between the interior and exterior of an air bubble is a function of the surface tension and diameter of the air bubble. The relationship is expressed as following:

$$\mathrm{D} = \frac{8\gamma}{\Delta P} \tag{3.6}$$

where, D is air bubble diameter (in m), γ is water surface tension (in N m^{-1}), and ΔP is the pressure difference inside and outside of the air bubble (in Pa). From equation (3.6), the diameter of an air bubble directly depends upon the water surface tension and is inversely related to the pressure differential inside and outside the air bubble. In other words, the greater the water surface tension, the larger the air bubble diameter. As mentioned earlier, in an irrigation system with a given model of air injector venturi, and for a given pressure differential at the inlet and outlet of the venturi, a certain volume of air in the form of air bubbles will be introduced into the irrigation pipe within a given time interval. When surfactant is added to the aerated water, the surface tension of water decreases and accordingly the diameter of the air bubbles will be decreased. Consequently, the total number of air bubbles will be increased in contrast to the case where no surfactant is used in the irrigation water (Rosenblit et al. 2006). Simultaneous reduction in the diameter and increase in the number of air bubbles will lead to two main outcomes. First, the increased number of air bubbles will result in availability of relatively more air bubbles to the distal emitters thereby improving the uniformity of the air flow distribution along the pipe. Second, formation of relatively small bubbles leads to a reduction in the delivery of air bubbles by emitters and hence a decrease in the magnitude of average emitter air flow rate along the pipe. This is explained as follows. Before addition of surfactant, there are a limited number of air bubbles at the beginning of the pipe, which are of relatively large diameter compared to the case when surfactant is added. The consequence of this situation is that the majority of the air bubbles will be discharged through the first few emitters resulting in high emitter air flow rates (because the air bubbles are large). However, almost no or very little air bubbles might be left for the remote emitters resulting in non-uniform distribution of the emitter air flow rates along a pipe. When surfactant is added to water, it reduces the diameter of air bubbles and hence increases the number of them. Part of the air bubbles will be discharged through the proximal emitters and there will be still some air bubbles for the remote emitters (because of the increased number of the air bubbles). Since the diameter of the air bubbles are relatively small (as a result of reduction of the water surface tension), the average emitter air flow rate (particularly those contributed to the proximal emitters) will be smaller and the uniformity of the emitter air flow rates will be relatively better.

In a recirculating irrigation system, simultaneous reduction in the diameter and number of air bubbles as a result of addition of surfactant into the irrigation water might lead to a corresponding decrease in efficiency of air bubble delivery via loss of relatively more air bubbles from the end of the pipe.

3.4.3 Preferential path for air flow (Trial 3)

The results mentioned in section 3.3.3, are explained by the ‘first relative low pressure zone encountered’ concept. Air bubbles supplied by the venturi are pressurized while flowing within the irrigation pipe. The pressure varies between 76 kPa (11 psi) as measured at the outlet of the venturi and 62 kPa (9 psi) at the end of the lateral before returning to the irrigation tank. In Figure 3.6, the pipe diameter and the amount of fluid flowing through the main pipe were larger than those in each lateral pipe. Hence, the pressure at the junction point of the main pipe to the manifold was greater than the pressure at the beginning of either lateral pipe. It is most likely the air bubbles first entered into the two middle laterals, because they were closest to the junction point. As the air bubbles entered into the middle laterals, part of the air bubbles were discharged through the upstream emitters and resulted in the creation of a relatively low pressure zone in these laterals. Subsequently, a pressure gradient formed between the junction point and the first emitters on the middle laterals. The entire air bubbles were probably forced towards these relative low pressure zones via the pressure gradient. Hence, for an infinitesimal time interval, due to discharge of some air bubbles from the emitter on the closest laterals to the junction point, a relative low pressure zone was created in contrast to the distal laterals where air bubbles had not yet reached. The same reason explains the preferential flow of the air bubbles in Figures 3.7 and 3.8.

The behaviour of air and water flow (two-phase flow) in parallel pipes with common inlet and outlet manifolds is quite complex and it is difficult to predict how the two phases are distributed among the pipes (Pustylnik, Barnea & Taitel 2006). In a two-phase flow with a branching pipe system, distribution of the phases among the pipes is very complicated and depends upon the junction geometry, pipe slope, length and diameter of the pipe, inlet flow rates and their physical properties (Tshuva, Barnea & Taitel 1999). It has been shown that two-phase flow may split unevenly when entering a parallel piping system (Hetsroni et al. 2004). Taitel et al. (2003) studied the distribution of two-phase flow (water and compressed air) in four parallel Plexiglass pipes for four inclination angles 0°, 5°, 10°, and 15°. The diameter and length of the pipes were 26 mm and 6 m, respectively. The pipes were 60 cm apart with common inlet and outlet manifolds of 50 mm ID. Water flow rates in the range of 0.05-3 L s^{-1} and air flow rates of 0.1-3 L s^{-1} were tested. For the horizontal case, two-phase flow occurred in all four pipes. For the inclined pipes, various flow configurations were obtained. For low flow rates of air and water, two-phase flow took place only in a single pipe while the other pipes were partially filled with stagnant column of water. As the rates of air and water were increased, two-phase flow was observed in two, three, and eventually in all the four pipes. Pustylnik, Barnea and Taitel (2006) proposed an analytical approach based on steady state solution of a momentum equation for prediction of the number of pipes with stagnant water column as a result of asymmetric flow of air and water in a system of parallel pipes. It is noteworthy that in drip irrigation systems with parallel piping layouts, such as those tested in this experiment, there are numerous emitters on lateral pipes which cause alteration in the hydraulic characteristics of the phases (e.g. velocity and pressure). Moreover, in contrast to the experiments conducted by Taitel et al. (2003) and Pustylnik, Barnea and Taitel (2006), where phase split in the inlet manifold led to partially filled stagnant water columns in several pipes and two-phase flow in the other lines, flow of pressurized water only, or air and water was always observed in my trials. Hence, the method proposed by Pustylnik, Barnea and Taitel (2006) should be modified for pipes with emitters for prediction of asymmetric flow in drip irrigation systems with parallel lateral lines.

3.4.4 Air flow rate distributions from pressure compensated on-line pot drippers with long asymmetric connectors (Trial 4)

3.4.4.1 Air flow rate distributions in the absence of goof plugs, with or without surfactant

Figure 3.25 and data mentioned in subsection 3.3.3.1, indicate that except for the first sampling location, water flow rates were not affected by either air flow or addition of surfactant. The extraordinary high air flow rates in the first few emitters displaced water and resulted in an abrupt drop in water flow rates from these emitters. Water flow rates from the emitters proximal to the venturi were less than the nominal flow rate (i.e. 1.2 L h^{-1}) of these emitters. The displacement effect from the high air flow rates was limited to a short distance of approximately 8 metres from the venturi (Figure 3.26). Due to the limited range of the effect of the high air flow rates on water flow rates, the mean water flow rate and the associated CUC were not remarkably smaller than those measured for the water alone and water with air and surfactant treatments.

The drop off in the water flow rates of the first few emitters suggests that the macro air bubbles discharged from the proximal emitters must have been of relatively large diameter such that they hindered instantaneously the free flow of water from the emitters, thereby reducing the nominal water flow rate of the emitters. For the other emitters (i.e. the distal ones), the diameters of the air bubbles were probably too small to hinder to the flow of water. It follows that for the current irrigation settings, the majority of the air volume supplied by the venturi was discharged through the emitters just down to 8 metres from the venturi.

Addition of surfactant to the irrigation water markedly improved the distribution of air flow rates. Surfactant reduced the average air flow rate discharged from the proximal emitters, which in turn led to availability of more air bubbles for the distal emitters. This in turn enhanced the CUC of the air flow rates by 145% relative to that without surfactant. In section 3.4.2, the effect of surfactant on the number and diameter of air bubbles was discussed in detail.

Figure 3.27 shows air flow rate distribution without surfactant; and from Figure 3.26 it is clearly evident that almost all the air bubbles supplied by the venturi were discharged unevenly over a short distance comprising just 4% of the total pipe length. In contrast to the case without surfactant, Figure 3.28 shows three distinctive zones indicative of the varying availability of air bubbles to the emitters along the pipe. Zone 1 shows the range over which a high rate of air flow was maintained steadily. In fact, addition of surfactant led to a proportionate increase in the number of air bubbles over a longer distance from the venturi. The local turbulence from the asymmetric connectors resulted in a further increase in the availability of air bubbles such that every connector within this zone was able to deliver the maximum recorded air flow rate, i.e. about 0.4 L h^{-1}. In other words, the potential delivery of air flow rate for the asymmetric connectors within zone 1 was about 0.4 L h^{-1}. Zone 2 shows a uniformly linear decline in the trend of the air flow rate distribution. In fact, the reduction in the flowing air volume as well as the gradual reduction in water pressure resulted in accordingly weaker turbulence from the connectors in this zone. Due to the foregoing reasons, the connectors were no longer able to maintain the so called potential delivery of air flow rate. In zone 3, despite the presence of surfactant and the turbulent effect of the asymmetric connectors, there were no macro air bubbles left in the pipe to be delivered to the emitters. It should be noted that although reduction in water pressure is expected to result in corresponding enlargement in the diameter of air bubbles, it seems that the size as well as the quantity of the air bubbles were too small for the 9.5 mm long asymmetric connectors to be delivered to the emitters in zone 3. In all these experiments, the volume of the suspending micro air bubbles within the sampled water was ignored, as the simple technique employed for collection and measurement of air bubbles was not able to measure them. Moreover, since the accuracy of the measuring cylinder (for measuring the volume of discharged air from the emitters) was ±10 mL, it is likely that the volumes of the sampled air at the remote sampling locations of the pipe were less than 10 mL.

3.4.4.2 Air flow rate distributions in the presence of goof plugs, with or without surfactant

Utilization of goof plugs clearly enhanced the uniformity of air flow rates, particularly in conjunction with surfactant. The enhancive effect of the goof plugs was due to the additional turbulence created around the tip of the goof plugs (Figure 3.48) which were just few millimetres away from the connectors. The resulting turbulence increased the availability of air bubbles to the connectors. However, a comparison between Figures 3.28 and 3.30 clearly reveals that goof plugs alone improved the uniformity of air flow rate distribution less effectively than surfactant alone. It is likely that the marked improvement was due to the increased availability of air to the emitters (by goof plugs) and the increased number of air bubbles (by surfactant).

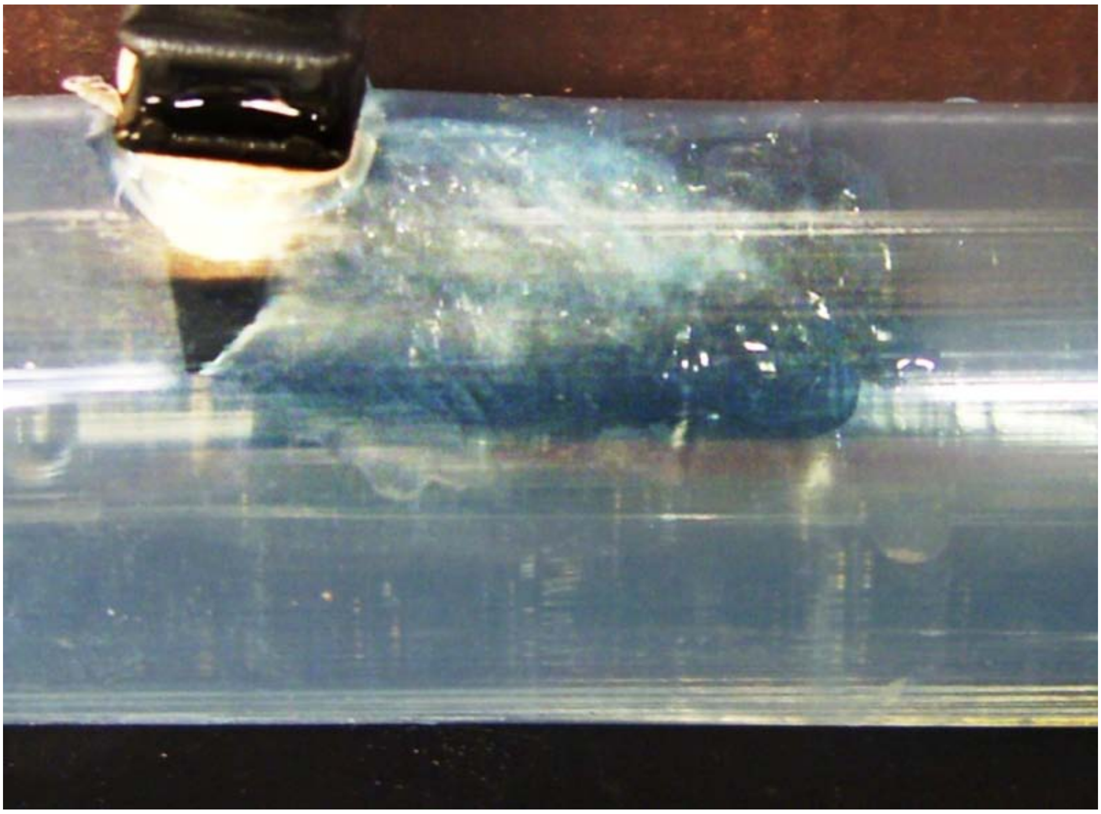

Figure 3. 48 The turbulence created by a goof plug.

There were two important outcomes from the increased enhancement of the air flow rate uniformity. First, the range of zone 1 (i.e. the zone of uniform high air flow rates) in Figure 3.31 was more than two fold longer than that in Figure 3.28 (i.e.

67% vs. 31%). Second, the range of zone 2 (i.e. the zone of declining air flow rates) in Figure 3.31 was more than 2.5 fold shorter than that in Figure 3.28 (18% vs. 46%).

Overall, the goof plugs further enhanced the effects of asymmetric connectors and surfactant on the uniformity of air flow rate distribution.

3.4.5 Air flow rate distributions from pressure compensated on-line pot drippers with long symmetric connectors (Trial 5)

3.4.5.1 Air flow rate distributions in the absence of goof plugs, with or without surfactant

From Figure 3.33, it was hypothesized that the delivery of water and air bubbles caused a corresponding reduction in the water pressure, and consequently enlargement of the air bubbles in the beginning of the pipe. This led to an increase in the submerged length of the connectors (SLC) in that location of the pipe. Possibly, the greatest increase occurred 15 m from the venturi, where largest emitter air flow rate was recorded. From this point onward, further delivery of water and air bubbles resulted in further reduction of water pressure but owing to the fixed supply of air flow (from the venturi), less air bubbles were available for the distal emitters.

Comparing Figures 3.33 and 3.36 (symmetric connectors) with Figures 3.27 and 3.30 reveals a distinct difference between the functionality of the symmetric connectors and the asymmetric ones. For the asymmetric connectors (Figures 3.27 and 3.30), the maximum air flow rate occurred at the first sampling location, whereas for the symmetric ones, the maximum air flow rate took place somewhere other than the first sampling location. Moreover, it turned out that the symmetric connectors in the absence of surfactant yielded a higher uniformity in the distribution of air flow rates in contrast to the asymmetric ones. This is explained by the fact that asymmetric connectors benefited from two factors for access to air bubbles. One factor was the SLC, and the other was the pressure differential at the tip of an asymmetric connector. These two factors conjointly led to augmented availability of air bubbles to the asymmetric connectors in comparison with the symmetric ones. Owing to the fixed amount of air flow supplied by the venturi (for a given pressure differential), the augmented availability of air bubbles to the asymmetric connectors caused augmented uneven distribution of air flow rates along the pipe as a result of high air flow rates from the proximal emitters but low air flow rates from the distal emitters. In contrast, symmetric connectors benefited from only one factor for access to air bubbles. Hence, for the same pressure differential across the venturi, the magnitudes of maximum air flow rates from symmetric connectors were smaller than that from asymmetric ones.

Addition of surfactant reduced the surface tension of water, thereby reducing the diameter of air bubbles as well as increasing the number of air bubbles. The relatively steep slope of the air flow rate distribution within zone 1 in Figure 3.34, suggests that the decrease in the depth of the region occupied by air bubbles might have occurred faster than the associated reduction in water pressure (as a result of air and water delivery). In contrast to zone 1, less air bubbles were available to the emitters in zone 2 due to delivery of air bubbles over a relatively longer distance from the venturi. However, it is likely that the reduced availability of air bubbles in zone 2 was offset to some degree via further enlargement of the air bubbles as a result of further reduction in water pressure in that zone. This might explain the mild slope of the air flow rates in zone 2.

3.4.5.2 Air flow rate distributions in the presence of goof plugs, with or without surfactant

Insertion of goof plugs in front of the symmetric connectors improved the availability of air bubbles to the emitters, in the same way as they did to the asymmetric connectors. However, the situation in Figure 3.36 is much more complicated than that in Figure 3.33. In Figure 3.36, three zones are distinguishable. The declining trend of emitter air flow rates in zone 1 might be attributed to delivery of air bubbles. Possibly, the pressure in the short range of this zone was too high to allow for a significant increase in the diameter of the air bubbles resulting from the delivery of air bubbles in that zone. Within zone 2, as air bubbles flowed downstream, further delivery of water and air bubbles led to significant enlargement of air bubbles as a result of reduction in water pressure. Figure 3.36 suggests that the largest SLC occurred at 80 m from the venturi, where the greatest emitter air flow rate was recorded. In contrast to zone 2, further reduction in water pressure within zone 3 was not accompanied by an increase in emitter air flow rate. This might be attributed to the decreasing depth of the region occupied by air bubbles (due to the limited volume of air supplied the venturi) relative to the length of the connectors.

The similarity in the trend of air flow rates for symmetric connectors in the presence of goof plugs and surfactant, with the trend for asymmetric connectors under the same conditions suggests that the conjoint effect of goof plugs and surfactant overrode the effect of the geometry of connectors. In other words, while addition of surfactant increased the number of air bubbles, insertion of goof plugs immediately before the symmetric connectors improved availability of air bubbles to the remote emitters.

3.4.6 Air and water flow rate distributions from non-pressure compensated on-line pot drippers with short symmetric connectors (Trial 6)

Despite a high aeration rate of approximately 280% at the first sampling location (Figure 3.39), it is evident from Figure 3.38 that water flow rate at this location did not drop off. This is attributed to the type of the emitters used in this trial. As the emitters were non-pressure compensated, water flow rate was a function of pressure; the higher the pressure, the greater the water flow rate from the emitters. Hence, in contrast to the pressure compensated emitters, a high emitter air flow rate did not effectively influence the emitter water flow rate at the first sampling location.

Addition of surfactant to the irrigation water resulted in the formation of two distinct zones in the trend of aeration rates; zone 1 with a linear decrease in the aeration rates extending about 150 m from the venturi, and zone 2 with an almost zero aeration rate (Figure 3.40). The trend in distribution of emitter aeration rates in Figure 3.40 looks very similar to that of the emitter air flow rates presented in Figure 3.34, except that the former lacks the zone of abrupt decline. Possibly, the shorter protruded length of symmetric connectors used in section 3.2.2.2 in contrast to the longer ones in section 3.2.2.3, led to greater SLC over a longer distance from the venturi. It is likely that the non-pressure compensated emitters sustained the relatively high emitter aeration rates at the beginning of the pipe via delivery of more water and air under the high pressure within that location. In other words, under the high water pressure prevailing at the beginning of the pipe, the non-pressure compensating emitters accordingly delivered more water as well as air so that the relatively high emitter aeration rates over the beginning part of the pipe were sustained.

3.4.7 Air and water flow rate distributions from non-pressure compensated emitters on an integral dripperline (Trial 7)

Figure 3.41 clearly shows an abrupt drop in the water flow rate in the first sampling location for the air and water treatment. Although the drippers used in this trial were non-pressure compensated, the thickness of the integral drippers relative to the depth of the region occupied by air bubbles explains the dissimilarity between the outcomes resulting from the irrigation systems in Figures 3.38 and 3.41. As mentioned earlier, the availability of air bubbles to an emitter directly depends on the depth of SLC. Clearly, at a given sampling location, the SLC of a 2 mm thick dripperline emitter is much greater than that of a 7 mm long symmetric connector. Hence, it is likely that water was displaced by markedly higher air flow rates from the first emitters of the dripperline. The importance of SLC is further clarified by comparing the mean aeration rates resulted from 9.5 mm long symmetric connectors, 7 mm long symmetric connectors, and 2 mm thick integral emitters in the absence of surfactant and goof plugs. The mean aeration rates for the long connectors, the short ones, and the integral emitters were 14%, 28%, and 135%, respectively.

Distribution of the aeration rates with or without surfactant for the integral dripperlines was different from those with the non-pressure compensated pot drippers. There are two reasons for this dissimilarity. First, as mentioned in the previous paragraph, the 2 mm protruded length of the integral dripperlines had access to more air bubbles than did the symmetric connectors with 7 mm protruded length. Second, according to Mazzei Injector Corporation Performance Table (n.d.), the estimated volume of air supplied by venturi model 484 to the pot drippers was 120.2 L h^{-1}, whereas the estimated volume of air supplied by venturi model 384 to the integeral dripperline was 52.4 L h^{-1}.

In all these trials, the distribution of the air bubbles was non-uniform along the irrigation pipe, particularly when pure water was used. This is in agreement with the non-linear trend in the yield of oxygated bell peppers along the lateral lines reported by Goorahoo et al. (2002). They mentioned a positive effect of oxygation on the yield of bell peppers from the beginning of the lateral to a maximum at 28 m (81 feet) location. The yield then decreased down the lateral to a minimum value at the 51 m (168 feet) location, while the laterals were 85 m (190 feet) long. Goorahoo et al. (2002) did not measure the emitter air flow rates (or aeration rates) along the laterals; however, it is likely that the non-uniform trend in the yield of the aerated treatment along the drip tapes was a result of the non-uniform distribution of air flow rate along the pipes.

In contrast to Goorahoo et al. (2002), Pendergast and Midmore (2006) reported no significant differences for any of the variables relating to the performance of cotton, in relation to position along the 230 m lateral. The type of drip tape used by Pendergast and Midmore (2006) was the same as the dripperlines used in this chapter. Nevertheless, they did not mention any data about the distribution of the emitter aeration rates. Hence, comparison in terms of the distribution of air bubbles along drip tape between the experiment conducted by Pendergast and Midmore (2006) and those in this chapter, cannot be made.

Low and non-uniform distribution of emitter air flow rates along irrigation pipes were the main problems in the efficacy of both recirculating and dead-end oxygation systems which use venturis for aeration of irrigation water. It was hypothesised that use of very low flow rate emitters instead of the conventional ones and addition of surfactant will alleviate the aforementioned shortcomings for the recirculating irrigation systems. However, this solution is not likely to work for dead-end systems. The reason is that the minimum motive flow rate to the inlet of a given size of venturi must be equal to or greater than the sum of water flow rate of the entire emitters in the irrigation system. This is illustrated by the following example. Assuming in a dead-end irrigation system with 410 emitters each of 2 L h^{-1}, a Mazzei air injector venturi model 484 with minimum motive flow rate of 2×410 = 820 L h^{-1} introduces 256 L h^{-1} air flow rate into the lateral pipe (resulting in an aeration rate of $\frac{256 \times 100}{820} = 31\%$ aeration rate) provided that 276 kPa pressure differential is maintained across the venturi (Mazzei injector corporation, n.d.). If the 2.0 L h^{-1} emitters are replaced by emitters of 1.1 L h^{-1}, this will lead to reduction of the motive flow rate to 1.1×410 = 450 L h^{-1}. The venturi model 484 will not be able to supply the desired 256 L h^{-1} air flow rate to the system unless a motive water flow rate of at least 820 L h^{-1} is sustained at the outlet of the venturi. For the new motive flow rate, the same venturi (model 484) will be able to introduce only 17 L h^{-1} air flow rate (leading to $\frac{17 \times 100}{450} = 4\%$ aeration rate) provided that 34.3 kPa pressure differential is maintained across the venturi. In other words, 45% reduction in the water flow rate of the emitters ($\frac{2.0 - 1.1}{2} \times 100 = 45\%$) led to 87% $\left(\frac{31 - 4}{31} \times 100 = 87\%\right)$ reduction in the aeration rate of the water. However, theoretically, one solution to this situation (i.e. reducing the minimum motive flow rate without reduction in the air flow rate) might be making use of the preferential flow. Possibly, this could be achieved through a by-pass from the pipe AB connected to the outlet of the venturi (Figure 3.49), to return the excess flow to the irrigation tank. The length and slope of the pipe AB, and the diameter of the by-pass should be designed in a way that the preferential flow of the air occurs only into the lateral pipe and water (without air bubbles) enters

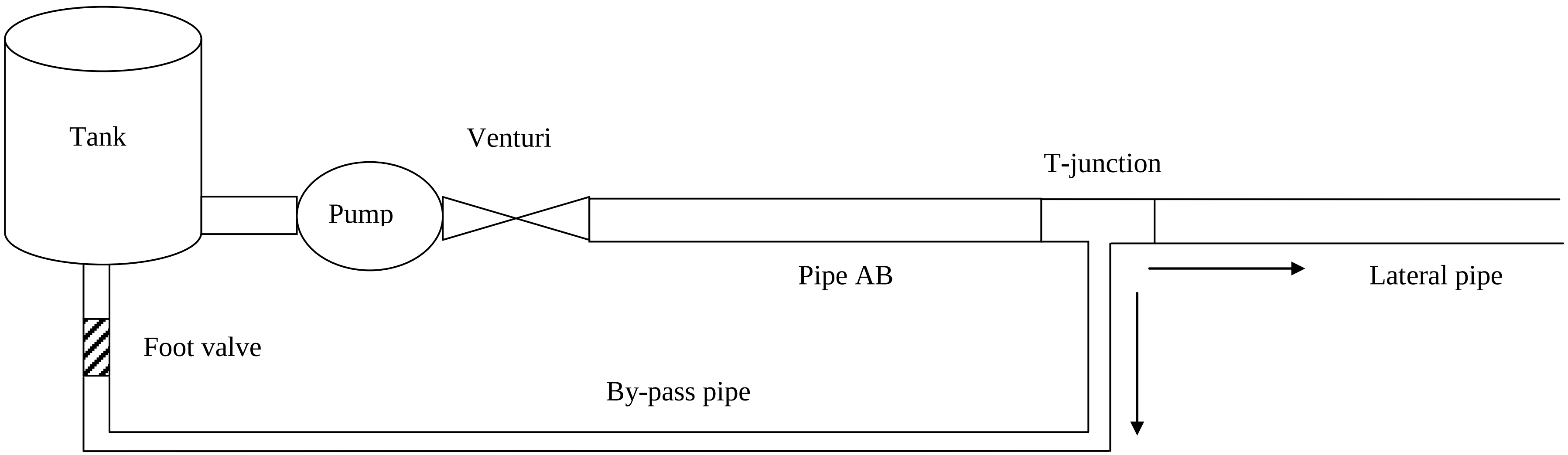

Figure 3. 49 Proposed layout for controlling the motive flow rate. The arrows indicate direction of flow.

into the by-pass. Furthermore, the position of the T-junction in Figure 3.49 should be such that the direction of the water flow from the T-junction into the by-pass pipe is downward.

It is interesting to note that in the oxygation experiments on the vegetable species (Chapter 6), wheat (Chapter 7), and soybean (Chapter 8) a declining trend on the crop yield and growth parameters was always observed along the irrigation pipe with the highest plant performance in the first block (the one closest to the air source). Moreover, the distribution of the emitter air flow rates along the irrigation pipe in the aerated treatments in the abovementioned chapters showed a declining trend similar to those in this chapter.

3.5 Conclusion

Average water flow rates were not affected by the cross sectional area of the emitters, nor by surfactant, nor by asymmetric goof plugs. However, in the absence of surfactant, the extraordinary high air flow rates at the beginning of the pipe generally depressed water flow rates from the first few emitters. Emitters of the large CSA showed poorer CUC and significantly larger average emitter air flow rates in comparison with those of the small CSA.

It was shown that the availability and supply of air bubbles to the symmetric connectors depended upon the depth of SLC. For the asymmetric connectors, in addition to this factor, the local turbulence created at the tip of the connectors was responsible for delivery of air bubbles to the emitters. Hence, asymmetric connectors delivered relatively higher average air flow rates than the symmetric ones. For irrigation systems with symmetric connectors, it was shown that the larger the pipe diameter, the lower the mean air flow rate as well as the aeration efficiencies, but the higher the CUC. Contrary to the symmetric connectors, for the asymmetric ones, an increase in the pipe diameter led to an increase in the efficiency of air bubble delivery and emitter mean air flow rate, but the CUC was accordingly reduced.

The results obtained from the range of surfactant concentrations in the trials with a recirculating irrigation system indicated that an increase in the concentration of surfactant was followed by a corresponding enhancement in the CUC, but a reduction in the mean air flow rate, the maximum air flow rate, and efficiency of air bubble delivery.

It was revealed that for the branching pipe systems tested in these trials, the air bubbles flowed into the first relatively low pressure zone(s) encountered. The relative low pressure zone(s) was (or were) always located closest to the junction point of the main pipe and the manifold for all the configurations tested in the trials.

Low uniformity in the distribution of air flow rates along the irrigation pipe was the most prominent feature of all the trials. Addition of surfactant generally led to a reduction of the average emitter air flow rate (for the pressure compensated emitters) or aeration rate (for the non-pressure compensated emitters). The same positive effects, but weaker in comparison with that of surfactant, were consistently observed as a result of the application of goof plugs in the irrigation systems. Regardless of the geometry of connectors, addition of surfactant together with the insertion of asymmetric goof plugs immediately before the connectors, resulted in the highest recorded air flow rate uniformities.

Based on the current study, it is recommended to limit the maximum length of 19 mm ID pipes to 40 m (measured from the venturi) to ensure that aeration rate of the irrigation water is maintained above 12% for 1.15 L h^{-1} non-pressure compensated emitters. Addition of surfactant at C_f = 32 ppm will allow to extend the maximum length of the lateral pipe to 120 m and maintain the aeration rate of irrigation water above 12% across the pipe.

It is recommended testing different formulations of non-ionic surfactants or combinations of two or more than two surfactants to obtain maximum enhancement in CUC for air flow rate distribution. Some important factors that should be taken into account when choosing surfactants are low CMC, high solubility in water, low toxicity for plants, animals and humans, and ability to be recycled, cost, public and regulatory perception, and biodegradability.

To avoid the risk of preferential flow of air bubbles in branching pipe systems, it is suggested to use small size venturis at the beginning of every lateral line instead of using a big venturi for a group of lateral pipes.

Chapter 4: Response of grain sorghum to different rates of root aeration

ABSTRACT

In poorly drained fine textured soils, occurrence of anaerobic conditions in the root zone shortly after irrigation or transient flooding might adversely affect optimum root functioning leading to a reduction in crop yield. Sufficient supply of air/oxygen to the oxygen-depleted rhizosphere will alleviate the hypoxia/anoxia. A pot experiment was carried out to explore the effect of three aeration rates: 24%, 12%, and 0% by volume on the yield and physiological response of grain sorghum (*Sorghum bicolor* L.) in a glasshouse. Owing to the completely randomized design of the experiment, the plants in the 12% aeration treatment were irrigated via two lateral pipes equally spaced from the manifold. The 24% and 0% aeration treatments were irrigated with three lateral pipes in a way that the interior lateral pipe in either treatment was closest to the junction of the main pipe and the manifold. An air injector venturi was used for the introduction of air into the aeration treatments. A recirculating subsurface drip irrigation system with pot drippers and symmetric connectors were used.

The odd number of laterals in the 24% aeration treatment caused a preferential air flow into the interior lateral pipe so that the other (exterior) two lateral pipes received no air flow. The average emitter air flow rate for the 12% and 24% aeration treatments was 0.11 and 1.66 L h^{-1}, respectively. The efficiency of air bubble delivery, the ratio of total air discharged from the emitters to the amount of air supplied by the venturi, for both aerated treatments was 3%. The low emitter air

flow rate and efficiency of air bubble delivery were due to use of symmetric connectors and the recirculating irrigation system.

There was no significant difference in the yield and growth parameters among the treatments at $P<0.10$. Generally, the 24% aeration treatment yielded the lowest plant performance in comparison with the other treatments. It was attributed to the supra-optimal water temperature of this treatment ranging from 33 to 37 ºC as a result of marked friction between the continuously circulating by-pass water and the wall of two 50 m long 13 mm coils.

4.1 Introduction

Grain sorghum is a summer growing grass native to Africa and Asia. In Australia, it is usually grown on heavy clay soil in Queensland and northern New South Wales and is used as a stock feed in the cattle, pig and poultry industries (NSW DPI 2005).

In heavy clay soils with poor drainage, shortly after irrigation or transient flooding, plant roots may suffer from insufficient oxygen owing to slow transfer of dissolved oxygen in the water-filled pore space of the soil (Drew & Lynch 1980; Muchow & Coates 1986; Drew 1992). When soil temperature is high and respiration by microorganisms is stimulated, soil oxygen can be completely depleted in less than 24 hours and anoxia occurs in the root zone (Erdmann & Wiedenroth 1988; Good & Paetkau 1992). Grain sorghum is reportedly tolerant to a short duration of waterlogging as most extensive areas of sorghum cultivation are found where annual rainfall is about 450-1000 mm (Whitmore 2000; Reddy & Hodges 2000; Hazeltine & Bull 2003).

Subsurface drip irrigation (SDI) is capable of alleviating the soil hypoxia/anoxia by providing air/oxygen to the oxygen-depleted plant root zone. This could be achieved by coupling air injector venturi(s) to suck air into the SDI system (Goorahoo et al. 2007b). It has been shown that 12% aeration (by volume) of irrigation water via air injector venturi significantly enhanced yield and growth of bell peppers (Goorahoo et al. 2002), vegetable soybean and cotton (Bhattarai et al. 2004), tomato (Bhattarai et al. 2006), and chickpea and pumpkin (Bhattarai et al. 2008).

The objective of this experiment was to explore the influence of different rates of aeration of irrigated water by air injector venturi on the yield and growth parameters of grain sorghum in a glasshouse.

4.2 Materials and Methods

4.2.1 Location, Soil and Crop Details

A pot experiment was undertaken in the glasshouse (67% of full sunlight) on grain sorghum (*Sorghum bicolor* L.) at the CQUniversity Australia, Rockhampton campus (latitude: 23º 22´ 0.345" S and longitude: 150º 31´ 0.53" E, and altitude: 10 masl) over the period of 2006-2007. The grain sorghum variety ‘MR43’ was directly sown on December 7, 2006 and harvested on March 31, 2007.

A black cracking clay, Vertisol (Australian Soil Classification System as 6AUG-12), sourced from a field in Alton Downs, Central Queensland, was filled in white pots 40 cm high and 26 cm in diameter, each lined with a black plastic bag. Field capacity for the soil was measured as 43 mm H_2O 100 mm^{-1} soil according to the procedure described by Brady and Weil (1999). Each pot was filled to 28 kg dry soil in order to maintain the bulk density at 1.3 g cm^{-3} to ensure uniform soil porosity before imposition of the treatments.

Sorghum was planted in pots arranged at 75 cm between and 26 cm within row spacing. Pots within the row were in contact with each other. Five seeds were sown into the pots at 1 cm depth, and thinned to three plants per pot 15 days after sowing (DAS). Each plot consisted of four pots accommodating 12 plants.

4.2.2 Irrigation Set up and Fertigation

All pots were fitted with Plastro™ (Plasto Asia Pacific Pty Ltd., Australia) pressure compensated drippers[1] placed 25 cm below the soil surface. The water flow rate of drippers was 1.1 L h^{-1} under an operating pressure range of 60-350 kPa (9-50 psi).

Soil moisture was measured every day at 0-10, 10-20, 20-30, and 30-40 cm prior to irrigation events in one pot per experimental plot by means of a calibrated Micro Gopher (Soil Moisture Technology Pty Ltd, Australia) capacitance sensor. Irrigation was imposed every day and the volume of irrigation water for each treatment was calculated based on the soil moisture deficit to bring the soil water content within the soil profile to field capacity. Hence, the volume of the applied irrigation water for each treatment was controlled by the irrigation time.

The nutrient requirement of the crop was supplied through fertigation using a Peter's Professional™ (Scotts Australia Pty Ltd., Australia) general-purpose water-soluble fertilizer containing 20% N, 8.7% P, 16.6% K, 0.01% B, 0.004% Cu, 0.05% Fe, 0.03% Mn, 0.001% Mo, and 0.003% Zn. The nitrogen portion of the fertilizer

[1] The use of product names in this research is not an endorsement of the company's product. These names are mentioned here primarily for the purpose of letting readers know where the relevant materials can be obtained.

consisted of 28% nitrate, 20% ammonium, and 52% urea. Fertigation was achieved at the rate of 0.5 g L^{-1} continuously throughout the growing season resulting in a total of 703 g fertilizer per treatment through 77, 69, and 66 allocations for the control, 12%, and 24% aeration treatment, respectively. Different rates of water uptake among the treatments were accounted for by irrigating the plots without addition of fertilizer to irrigation water on some occasions to make sure that the same amount of nutrients was supplied to all plots.

4.2.3 Experimental Design and Treatment Details

Treatments were imposed starting on 15 days after sowing (DAS). Mazzei™ air injector venturis (model 384, 12.7 mm threads) were used to achieve different levels of air injection into the SDI system. The experiment was laid out as a Completely Randomized Design with one factor - rate of aeration. Aeration was set at three rates consisting of 24%, 12%, and 0 % (i.e. control) making three treatments overall. The layout of the experimental plots is presented in Figure 4.1. The internal diameter of the main and manifold pipes was 19 mm each, and the diameter of the lateral pipes was 13 mm. Symmetric connectors of 7 mm length protruding inside the lateral pipe were used.

For the 12% aeration treatment, the pressure at the inlet and the outlet of the venturi was maintained at 241 and 69 kPa (35 and 10 psi), respectively. The irrigation pump used in the 12% aeration treatment was Onga™ model JSP 100, supplying maximum flow rate and pressure of 55 L min^{-1} and 373 kPa (54 psi), respectively. The layout of the 12% aeration treatment is shown in Figure 4.2. For the 24% aeration treatment, the pressure at the inlet and outlet of the venturi was maintained at 413 and 69 kPa (60 and 10 psi), respectively. The minimum water

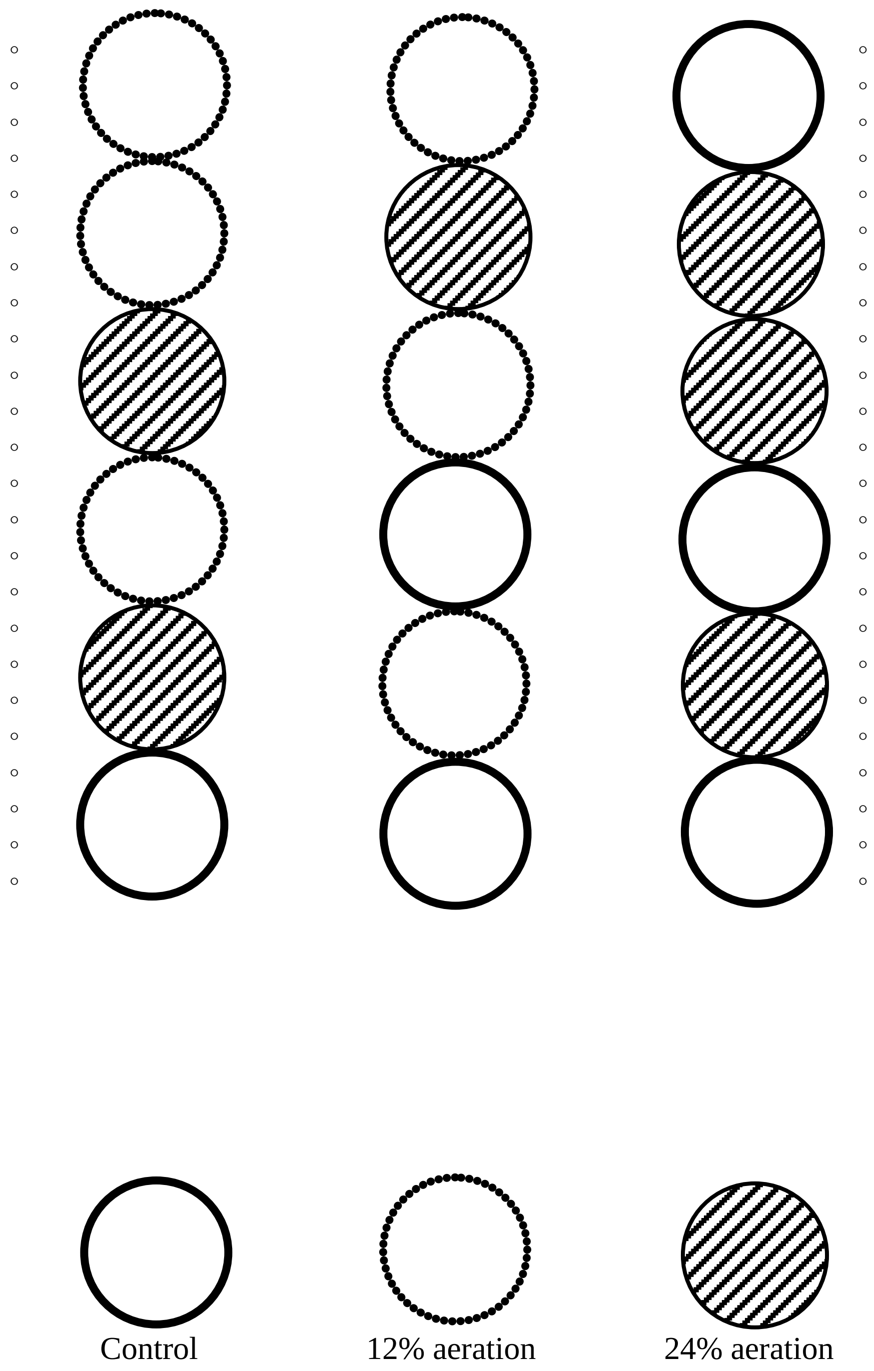

Figure 4. 1 The layout of the CRBD trial described in Chapter 4 (not to scale). Three oxygation treatments were imposed, with six replicate plots. Each large circle represents one experimental plot consisting of four pots, with each pot containing three sorghum plants. The small open circles denote the guard pots.

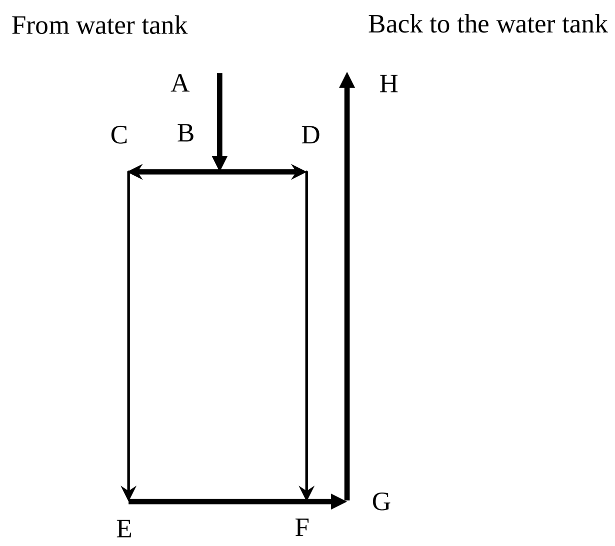

Figure 4. 2 Piping layout for the 12% aeration treatment. AB is a 19 mm diameter 3 m long main pipe, CBD and EF are manifolds of 19 mm diameter. CB and BD are 38 cm long, each. EF is 76 cm long. CE and DF are lateral pipes 800 cm long and of 13 mm diameter each. FGH is a return pipe of 1500 cm length and 19 mm diameter. CE and DF each supplied 12 drip emitters in series.

pressure within all laterals was maintained at 60 kPa (9 psi) during irrigation events. A Davey™ pump model V312L was used for the 24% aeration rate treatment, supplying maximum flow rate and pressure of 265 L min^{-1} and 1300 kPa (190 psi), respectively.

To maintain the inlet pressure for the venturi, the excess water flow before the venturi inlet was by-passed to the irrigation tank by two 13 mm ID white colour coiled pipes, each 50 m long. The continuous circulation of the excess water through the 13 mm by-pass pipes accompanied with the friction between the flowing water and the wall of the pipes warmed the water to approximately 35 ºC. To prevent a rise of water temperature in the 24% aeration treatment, both coils were submerged in the water tank. Water temperature in the irrigation tank before and after irrigation events was occasionally measured with a thermometer for all the treatments. Furthermore, to maintain the required outlet pressure at the venturi as well as the minimum operating pressure for the end emitter, the end of the pipe was fitted with a pressure gauge and tap and water and air bubbles were recirculated to the irrigation tank (piping layout for the 24% aeration treatment shown in Figure 4.3).

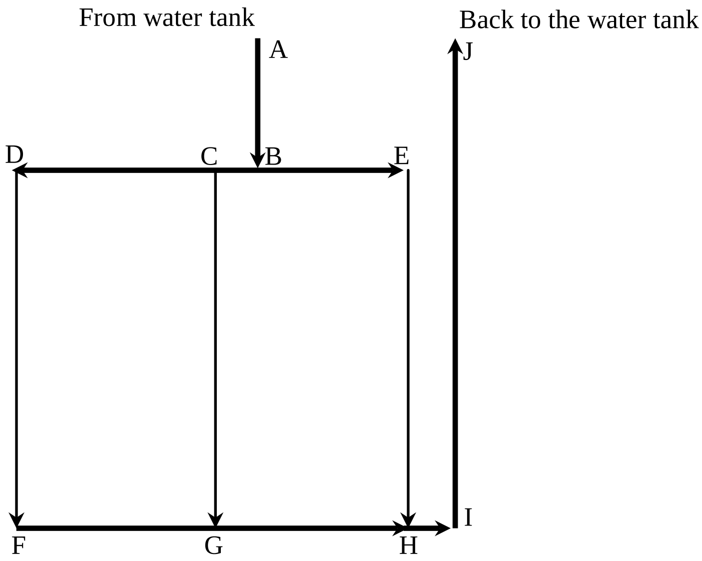

Figure 4. 3 Piping layout for the 24% aeration treatment. AB is a 19 mm diameter 3 m long main pipe, DCBE and FGH are manifolds of 19 mm diameter, each. DC = FG = GH = 75 cm, CB = 13 cm, and BE = 62 cm. DF, CG, and EH are lateral pipes of 13 mm diameter and 800 cm long, each. HIJ is a return pipe of 19 mm diameter and 1500 cm long.

For the control treatment, a Lowara™ pump model 2HM4 was used. The same piping layout for the 24% aeration was used for the control (Figure 4.3).

Soil temperature was recorded in one pot per plot by a calibrated temperature sensor Tiny Tag Ultra™ Model TGU-1500 (Gemini Data Loggers, UK) placed 25 cm below the soil surface.

The plants were infected with sorghum ergot, a fungal disease mainly caused by *Claviceps africana* (Frederickson, Mantle & De Milliano 1991) from 83 to 91 DAS. Sorghum ergot reportedly requires high relative humidity equal or above 90%

and a temperature range of 14 - 28 °C for optimal development (Futrell & Webster 1966). The ambient temperature and relative humidity inside the glasshouse during the period were 30 °C and 70%, respectively (data not shown). For better and efficient control of the disease, in addition to the use of Bayfidan™ (active ingredient: Triadimenol) at the concentration of 0.7 mL L^{-1}, no irrigation was done (to reduce the relative humidity) from 83 to 91 DAS.

SPAD readings (a surrogate for leaf chlorophyll concentration) were made using a Minolta chlorophyll meter (SPAD-502™), with measurements made on one fully expanded leaf for each plant in one pot per plot 73 DAS and then averaged.

Stomatal conductance, and leaf photosynthetic and transpiration rate were measured with an infrared gas analyser (IRGA) model LGA-4™ (ADC UK) on one fully expanded leaf per pot per plot between 1318-1449 h 80 DAS.

Canopy light interception was calculated by measuring the photosynthetically active radiation (PAR) with an AccuPAR™ ceptometer (Decagon USA) in one pot per plot between 1130-1215 h 78 DAS. In each plot, the ceptometer was placed at right angles to the crop row and two readings were taken and then averaged; each consisting of one reading above the canopy and four readings beneath the canopy. Percent canopy light interception was calculated as the relative difference between PAR above and beneath the canopy.

Crop water stress index (CWSI) was measured using a Model 210 Ag Multimeter™ (Everest Interscience Inc., Fullerton, CA) portable infrared thermometer. In each measurement, to avoid the influence of the soil background on the canopy temperature readings, the infrared thermometer was held above the plant canopy at an angle of 15 ºC below the horizontal so that only the plant parts were viewed by the infrared thermometer. The measurements were carried out between 1245-1315 h, 79 DAS.

Soil respiration rate was measured with an Environmental Gas Monitoring apparatus (EGM-3 from PP Systems, UK). For the soil respiration measurement, a cylindrical chamber was placed on the soil surface and the rate of increase in CO_2 within the chamber was monitored. Within the chamber, air was continuously sampled in a closed circuit through the EGM and the soil respiration rate was calculated by the analyser based on the IRGA principle (Parkinson 1981). The soil respiration rate was measured in one pot per plot about one hour after cessation of irrigation at 1300 h 96 DAS.

At the end of the growing season, crop yield and some crop parameters including number and weight of leaves, main stem, and root weight, shoot:root ratio, tiller weight, and panicle weight (all on a dry weight basis) were recorded. The collected data were subject to the analysis of variance at $P<0.10$ using GenStat version 10.1 (Lawes Agricultural Trust, Rothamsted Experimental Station).

After the experiment, the same piping layouts for the aeration treatments were reproduced in order to verify the efficacy of oxygation in the treatments. Air flow rate from each emitter was measured using inverted plastic bottles submerged into a bucket filled with water. The accuracy of the measuring cylinder was 10 mL. For a given time interval, the water replaced by air bubbles was measured. According to Archimedes Law, the volume of the discharged air bubbles is equal to the volume of the replaced water. This technique takes into account the volume of macro bubbles but ignores the volume of suspended micro bubbles in the sampled water. Efficiency of air bubble delivery defined as the ratio of total air flow rates discharged from the emitters to the air flow rate supplied by the venturi, was calculated for the aeration treatments. The procedure for measurement of total air flow rates from the emitters and total air flow rates supplied by the venturi is described in detail in the ‘Materials and Methods’ of Chapter 3 under sub-section 3.2.1.1.

4.3 Results

Soil water content was monitored at different depths for each treatment from 17 to 112 DAS. Soil moisture within the upper half of the soil profile in all treatments was less than the field capacity, while the soil water content in the lower half of the soil profile was above the field capacity (Figure 4.4). Table 4.1 shows the average soil moisture for 0-10, 10-20, 20-30, 30-40 cm and within the entire soil profile for all the treatments. The average soil moisture (n = 64) within the entire soil profile of the control, 12% aeration, and 24% aeration was 41.2 ± 0.20, 40.9 ± 0.17, and 40.8 ± 0.17 mm H_2O 100 mm^{-1} soil, respectively, representing great homogeneity between treatments.

Soil temperature of a representative pot from each treatment was recorded over the course of a representative day. The average soil temperature (n = 94) for the control, 12% aeration, and 24% aeration was 26.6 ± 0.18, 26.8 ± 0.16, and 35.6 ± 0.33 °C, respectively (Figure 4.5). From 0244 h until 1800 h, the average soil temperature (n = 62) measured in the control, 12% aeration, and 24% aeration was 26.0 ± 0.23, 26.1 ± 0.18, and 33.6 ± 0.17 °C, respectively. There was a 7.5 °C difference in the soil temperature between the 24% aeration treatment and the other two treatments in this period. At 1808 h, the 24% aeration, 12% aeration, and the control were irrigated for 178, 182, and 137 minutes, respectively. From 1800 h until 0159 h (the next day), a marked rise in the soil temperature for the 24% aeration treatment and a slight rise in the temperature of the control and 12% aeration were

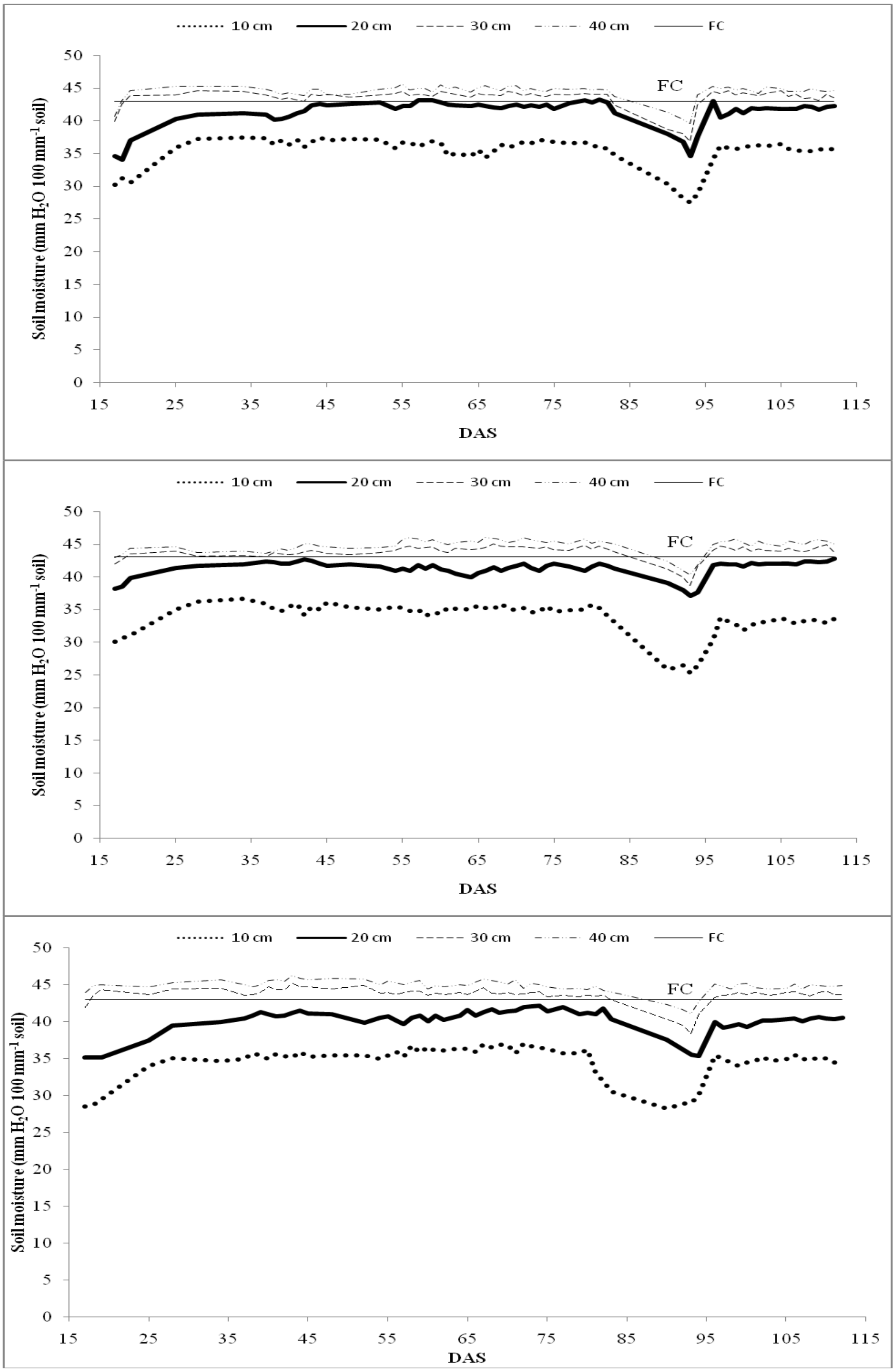

Figure 4. 4 Soil moisture variation in the control (top), 12% (middle), and 24% (bottom) treatments measured from 17-112 DAS.

Table 4. 1 Soil moisture (in mm H_2O 100 mm^{-1} soil) measured at different depths for three aeration treatments. The values are means and standard errors.

Treatment	0-10 cm	10-20 cm	20-30 cm	30-40 cm	Mean
Control	35.4 ± 0.28	41.4 ± 0.26	43.5 ± 0.18	44.5 ± 0.14	41.2 ± 0.20
12% aeration	33.7 ± 0.31	41.3 ± 0.15	43.8 ± 0.14	44.8 ± 0.14	40.9 ± 0.17
24% aeration	34.7 ± 0.29	40.1 ± 0.22	43.7 ± 0.14	44.9 ± 0.11	40.8 ± 0.17

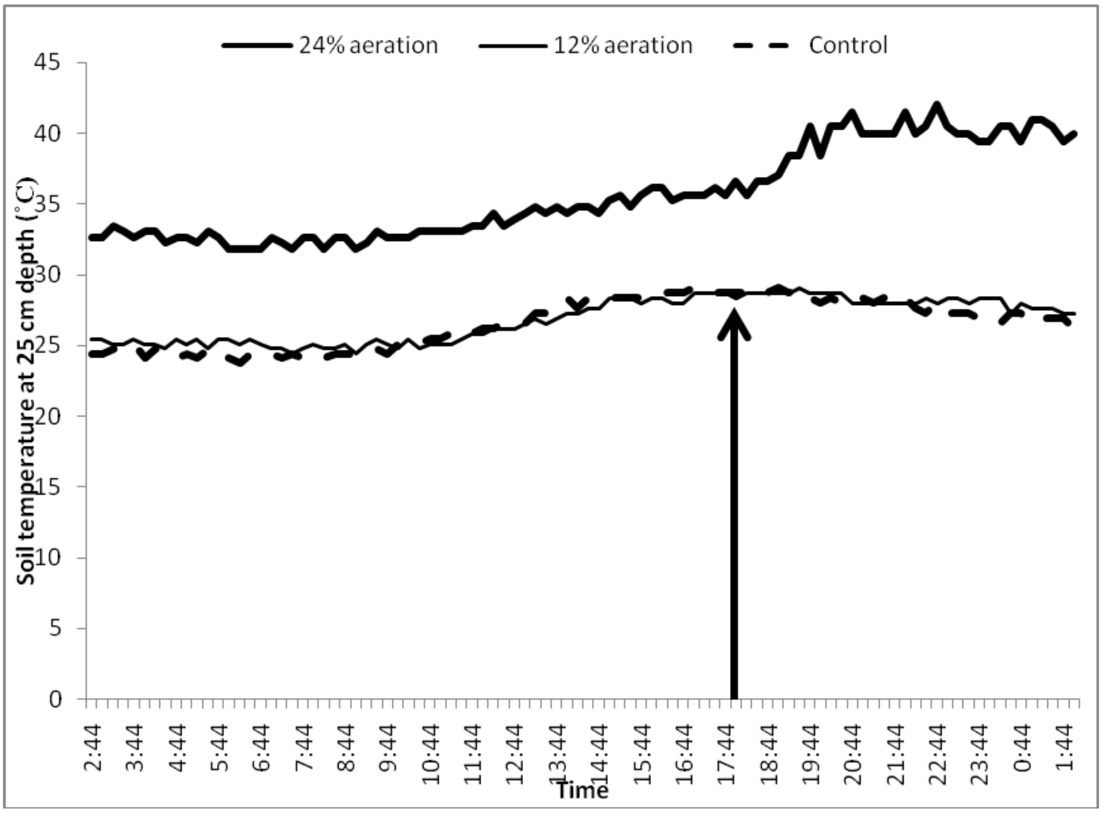

Figure 4. 5 Temporal variation of soil temperature measured in the treatments from February 21 to 22, 2007. The arrow indicates commencement of irrigation.

recorded. The average measured soil temperature (*n* = 32) for the 24% aeration, 12% aeration, and the control was 39.7 ± 0.26, 28.2 ± 0.09, and 27.7 ± 0.14 °C, respectively. This resulted in approximately 12 °C difference in the soil temperature between the 24% aeration and the other treatments.

At the end of the irrigation events, the range of water temperatures in the irrigation tank for the 24% aeration, 12% aeration, and the control was 33-37 °C, 30-

34 °C, and 30-34 °C, respectively, while water temperature in the irrigation tank at the beginning of the irrigation events for all treatments ranged between 28-32 °C.

Air flow rates from emitters as well as in the return pipe were measured for the aeration treatments. For the 24% and 12% treatments, the sum of air flow rates measured from the emitters was 6.66 L h^{-1} and 2.52 L h^{-1}, respectively. Total air flow rates supplied by the venturi for the 24% and 12% treatments measured at the return pipe were 207.1 L h^{-1} and 89.5 L h^{-1}, respectively. Hence, the calculated efficiency of air bubble delivery was just 3% for both aeration treatments which implies that in both treatments 97% of the total air supplied by the venturi was not deliverable by the emitters. It should be noted that for the 24% treatment, air bubbles were observed solely in the lateral pipe CG, while there was no air flow in either DF or EH (Figure 4.3). The average air flow rate in CG was 1.66 L h^{-1}. In contrast to the 24% treatment, air bubbles were observed in both lateral pipes for the 12% treatment. The average air flow rate for both laterals was 0.11 L h^{-1}. Emitter water flow rates from each lateral were measured for all the treatments (Figure 4.6). Comparison of the average emitter water flow rate from the lateral pipes with the nominal emitter water flow rate (1.1 L h^{-1}) indicated no significant difference at $P<0.10$ (Table 4.2).

There was no significant difference between treatments in transpiration rate, stomatal conductance, photosynthetic rate, canopy light interception, and CWSI or soil respiration rate (Table 4.3). A significant difference between treatments was recorded for the SPAD readings (Table 4.3). Leaf chlorophyll concentration in the control and in the 12% aeration was greater (significantly so for the control) than in the 24% aeration. There was also no significant difference between treatments in the number of leaves and the yield components, including shoot:root ratio and dry weights of leaves, main stems, tillers, heads, seeds, and roots (Table 4.4). It is

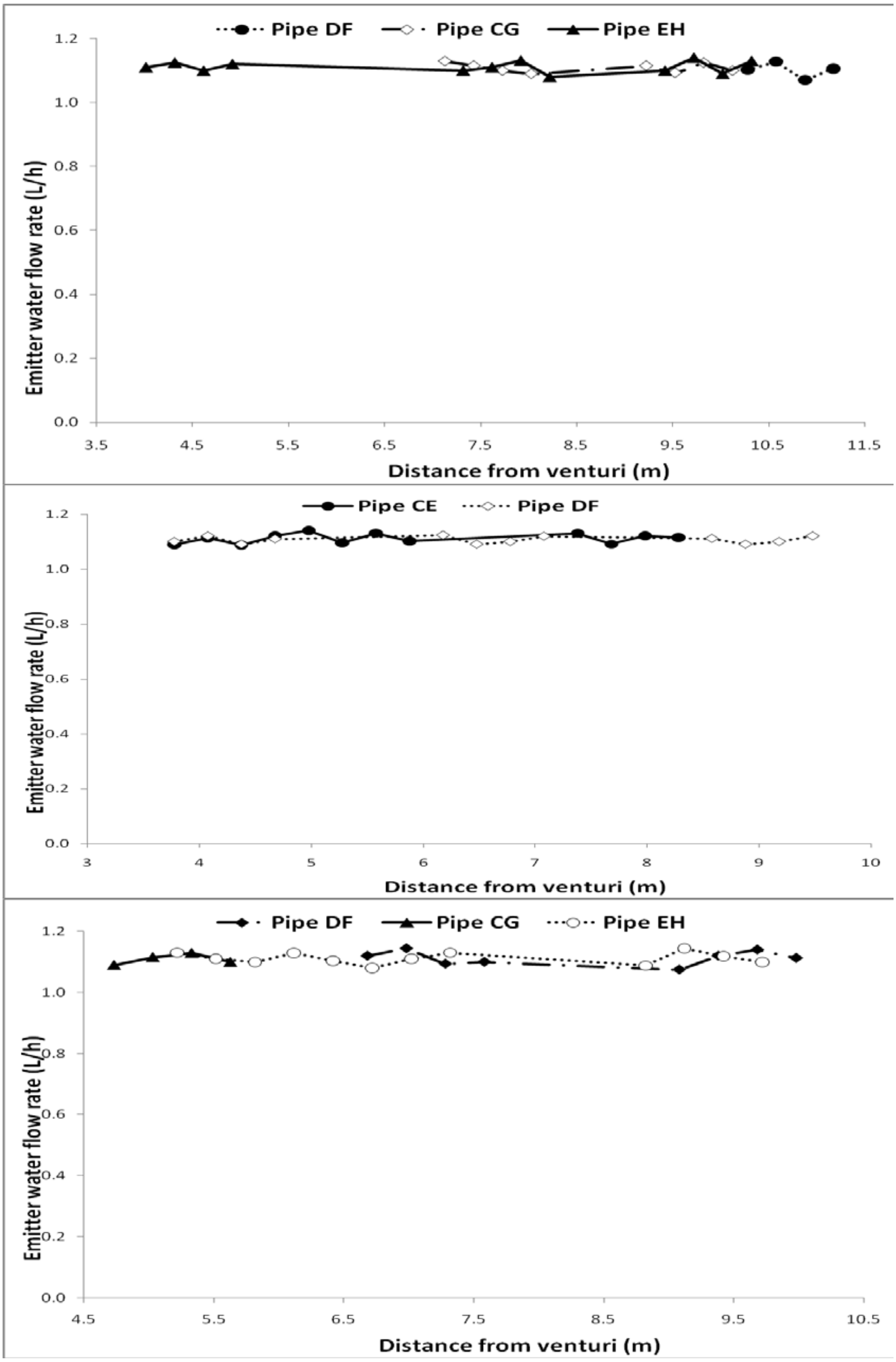

Figure 4. 6 Emitter water flow rates of the control (top), 12% aeration (middle), and 24% aeration (bottom) lateral pipes.

Table 4. 2 Analysis of the mean emitter water flow rates.

Treatment	12% aeration		24% aeration			Control		
Lateral pipe	CE	DF	DF	CG	EH	DF	CG	EH
Mean (L h^{-1})	1.11	1.11	1.11	1.11	1.11	1.10	1.11	1.11
Standard deviation	0.018	0.013	0.023	0.018	0.019	0.023	0.015	0.018
Standard error	0.005	0.004	0.008	0.009	0.006	0.012	0.005	0.005
T (P<0.05)*	2.073	1.702	1.609	1.018	2.148	0.157	1.633	2.143
Degree of freedom	11	11	7	3	11	3	7	11

*Critical t at P<0.05 for df 3, 7, and 11 are 3.182, 2.365, and 2.201, respectively.

Table 4. 3 Effect of aeration on the growth parameters for grain sorghum*.

Treatments	SPAD readings	Transpiration rate (mmol m^{-2} s^{-1})	Stomatal conductance (mmol m^{-2} s^{-1})	Rate of leaf photosynthesis (μmol m^{-2} s^{-1})	CWSI	Soil respiration rate (g CO_2 m^{-2} h^{-1})	Canopy light interception (%)
Control	57.8	1.56	0.036	19.5	0.31	0.614	91
12% aeration	54.7	1.41	0.036	14.8	0.40	0.664	83
24% aeration	47.0 (47.7)	1.74 (1.20)	0.044 (0.030)	17.6 (6.4)	0.34 (0.30)	0.540 (0.100)	92 (86)
LSD [df = 12]	9.37	0.510	0.0177	10.16	0.097	0.3602	7.79

*the values in parentheses indicate the measured values for the plot irrigated from the middle lateral of the 24% aeration treatment.

Table 4. 4 Effect of aeration on the yield components for grain sorghum*.

Treatments	Number of leaves	Leaf dry weight (g m^{-2})	Stem dry weight (g m^{-2})	Tiller dry weight (g m^{-2})	Panicle dry weight (g m^{-2})	Seed dry weight (g m^{-2})	Root dry weight (g m^{-2})	Shoot:Root ratio (on a dry weight basis)
Control	10.4	289.4	434	70.7	597	505	192.3	7.35
12% aeration	11.2	309.7	431	60.1	558	469	169.5	8.13
24% aeration	11.0 (10.0)	290.8 (269.0)	455 (421)	47.3 (57.4)	589 (487)	499 (417)	194.8 (185.7)	7.51 (6.67)
LSD [df = 12]	2.21	34.65	119.3	62.10	96.2	92.0	55.00	1.604

*the values in parentheses indicate the measured values for the plot irrigated from the middle lateral of the 24% aeration treatment.

evident that the only plot in the 24% aeration treatment that received aeration did not show any improvement in the measured foregoing parameters compared to the control or the 12% aeration treatment. The response of the plants in the 24% aeration rate treatment to aerated water delivered to the pots via lateral pipe CG is presented within parentheses in Tables 4.2 and 4.3.

4.4 Discussion

Soil temperatures were similar in the control and the 12% aeration treatments, while the 24% aeration showed a higher temperature following irrigation (Figure 4.5). Thus the 50 m long coiled by-pass pipes did not adequately serve as heat exchangers to prevent the rise of water temperature in the 24% aeration.

In the completely randomized design of the experiment, the 12% aeration plots were placed in two rows (Figure 4.1). Since the main pipe was connected to the middle of the manifold (Figure 4.2), the total head losses from the junction point B to the beginning of each lateral (points C and D) were the same; hence air bubbles flowed uniformly through both laterals. For the 24% aeration treatment consisting of three laterals (Figure 4.3), the junction of the main pipe and the manifold (point A) was closest to the middle lateral (i.e. pipe CG). From Figure 4.3, the lengths of DC, CB, and BE were 75 cm, 13 cm, and 62 cm, respectively. Clearly, the shortest route as well as the one with the least resistance to the flow of air bubbles was via the lateral CG. This explains why all the air bubbles only flowed into the middle lateral for the 24% treatment. In addition to the preferential flow observed in the 24% aeration treatment, both oxygated treatments showed low aeration efficiencies and low average emitter air flow rates. The low aeration efficiencies and the low emitter air flow rates are mainly attributed to the geometry of the connectors. In this experiment, symmetric connectors were used. In Chapter 3 sections 3.4.1.2 and 3.4.1.3, the performance of symmetric and asymmetric connectors is discussed in detail.

Nevertheless, neither the 12% aerated plots nor the plot oxygated by the middle lateral in the 24% aeration treatment (i.e. pipe CG in Figure 4.3) showed significant enhancement of growth, physiological parameters and yield compared to the control treatment. The only exception to this was the SPAD reading for leaf chlorophyll concentration which was close to being significantly less at 24% than that of the control and the 12% aeration.

The following reasons are proposed for the non-significant effects of aeration on sorghum in this experiment. First, grain sorghum (*Sorghum bicolor*) is moderately tolerant to waterlogging (Whitmore 2000; Reddy & Hodges 2000; Hazeltine & Bull 2003). Some species have the capability to oxidize their root environment when exposed to flooding conditions. The moderate tolerance of sorghum can be better understood by comparing its root oxidizing capacity with that of rice (*Oryza sativa*), a waterlogging-tolerant species, and maize (*Zea mays*), a waterlogging-sensitive species. The root oxidation capacity is expressed in terms of the amount of oxidized naphtylamine per gram weight of dry root. The oxidizing capacity of rice, sorghum, and maize are 15.3, 4.0, and 1.4 mg oxidized naphtylamine per gram of dry root per 48 h (Pimentel 2007).

Second, at a given pressure, the solubility of oxygen into water depends on the water temperature and electrical conductivity. Assuming an atmospheric pressure of 101 kPa, and water temperature of 30 °C (as at the beginning of irrigation for all the treatments), the solubility of oxygen (for fresh water) is 7.55 mg L^{-1} (Greenberg, Clesceri & Eaton 1992). The average water temperature at the end of the irrigation events for the control and 12% aeration was 32 °C and for the 24% aeration 35 °C. Hence, at the end of the irrigation the oxygen solubility for the control and the 12% aeration decreased to 7.30 mg L^{-1} while that of the 24% aeration reduced to 6.94 mg L^{-1} (Greenberg, Clesceri & Eaton 1992). This follows that the relatively higher average emitter air flow rate in the 24% aeration treatment was counteracted by less oxygen solubility in the irrigation water for this treatment.

Third, the relatively higher soil temperature in the 24% aeration treatment not only led to the reduction in the solubility of oxygen in the irrigation water, but also adversely affected root functioning and plant growth (Tables 4.3 and 4.4). The adverse impacts of supra-optimal soil temperature on sorghum growth are in agreement with other work on sorghum as well as other monocotyledonous species. Clark and Reinhard (1991) explored the effect of soil temperature on root and shoot growth traits of sorghum genotypes. They exposed four sorghum genotypes (SC33-9-8-E4, TX7000, SC118-15E, and TX428) to four soil temperatures 12, 17, 22, and 27 °C. Based on their findings, the soil temperature for optimum shoot and root growth was about 22 °C, with temperatures less than or above 22 °C resulting in inferior crop performance (i.e. relatively less root or shoot weight). In contrast to the control and the 12% aeration treatments, the elevated temperature of the irrigation water in the 24% aeration treatment resulted in a higher soil temperature and hence most likely suppressed root and shoot growth of the plants in the latter treatment.

Xu and Huang (2001) examined growth responses of two creeping bentgrass cultivars, L-93 and Pencross, to soil temperatures. The cultivars were exposed to (i) optimal soil and air temperatures (20/20 ºC, control), (ii) reducing soil temperature by 3, 6, and 11 ºC from 35 ºC at high air temperatures (32/35, 29/35, and 24/35 ºC), and (iii) high soil and air temperatures (35/35 ºC). Shoot growth rate, root:shoot ratio, and leaf chlorophyll content increased as soil temperature was lowered from 35 to 32 ºC, to a greater degree for Pencross than for L-93. Moreover, significant enhancement in clipping yield, root fresh weight, tiller density, and root number were not detected until soil temperature was lowered to 29 ºC. When soil temperature was lowered to 24 ºC, root:shoot ratio, quality of turf, and rate of shoot growth did not significantly differ from the corresponding parameters in the control.

Tahir, Nakata and Yamaguchi (2005) studied responses of three wheat genotypes, Imam, Fang, and Siete Cerros, to three sets of temperature conditions during the grain-filling period: (i) normal air temperature/normal soil temperature (26/26 °C), (ii) normal air temperature/high soil temperature (26/38 °C), and (iii) high air temperature/high soil temperature (38/38 °C). The 26/38 °C and 38/38 °C treatments significantly decreased the chlorophyll content (SPAD) of flag leaves, grain filling duration, and carbohydrate remobilization. Also, grain yield, biomass, grain weight, grains number spike^{-1} and harvest index at the 38/38 °C treatment were significantly lower than at the other two treatments. Therefore the reduced SPAD readings at 24% aeration are most likely due to the higher soil temperature in that treatment, given that irrigation and heating associated with it was repeated daily.

4.5 Conclusion

In this glasshouse experiment, the use of a recirculating oxygation system combined with symmetric connectors resulted in the delivery of a minute portion of the total air flow (supplied by the venturis) through the emitters. Most likely, the resulting aeration efficiencies from the oxygation systems were too small to significantly enhance the crop yield or crop components compared with the control treatment. Moreover, the experiment layout resulted in an odd number of laterals (i.e. 3) for irrigation of the 24% aeration treatment, which in turn caused a preferential air flow in the lateral closest to the junction point of the main pipe and the manifold. However, the imperfect cooling system for the by-pass flow of the 24% aeration treatment led to supra-optimal water temperature. The elevated water temperature remarkably reduced the oxygen solubility of the aerated water which in turn may have offset the effect of oxygation to the aerated plot. It also raised the soil temperature considerably, above that reported as optimal for sorghum.

Chapter 5: Effect of emitter depth, emitter cross sectional area and aeration rate of water on capsicum growth and fruit yield

ABSTRACT

A pot experiment was carried out in a screen-house to explore the effect of three levels of water aeration rate, two types of emitter depth, and two emitter cross sectional areas (CSA) on capsicum (*Capsicum annuum* L.) grown on a black cracking clay soil. The aeration rates (on volume basis) consisted of 0% (control), 12%, and 23%, the emitter depths were 5 and 20 cm from the soil surface, and the emitter cross sectional areas were 0.52 mm^2 (1.2 L h^{-1}) and 1.25 mm^2 (4.0 L h^{-1}). A branching pipe layout was used for the irrigation system. Irrigation was imposed to maintain the soil moisture close to 54 mm H_2O 100 mm^{-1} soil. Irrigation time depended on soil water content and emitter water flow rate.

Plants irrigated by shallow emitters performed significantly better than those irrigated by deep emitters. Possibly, the lower relative gas diffusivity (RGD) as a result of higher soil water content in the deep emitter treatment compared to the shallow emitter treatment, might have been responsible for the significant differences.

No significant effect was observed between the emitter types; however, plants irrigated by the low flow rate emitters (CSA = 0.52 mm^2) generally showed enhanced performance in contrast to those irrigated by the high flow rate emitters (CSA = 1.25 mm^2). One explanation could be that in the treatments irrigated with high flow rate emitters, the faster increase in the soil water content (over three times faster) followed by lower RGD led to poorer soil respiration and crop performance

compared to the treatments irrigated with low flow rate emitters. Evidently, the higher the soil water content, the lower will be gas diffusivity in the root zone, and the greater impairment to root respiration.

Aeration treatments had no effect on plant growth in either aerated treatments. This result is ascribed to a flaw in the design of the irrigation system, with the air supplied by the venturi flowing into the return pipe and returned back into the water tank without going into any of the laterals, suggesting a preferential flow of air because of the branching pipe layout.

5.1 Introduction

Capsicum (*Capsicum annuum* L.) is a fairly shallow-rooted vegetable species and has a low tolerance to drought or flooding. In order to get high productivity, the crop requires a sufficient supply of water and relatively moist soil over the growing season (Rezende et al. 2003). In a glasshouse experiment, Urrestarazu and Mazuela (2005) explored the influence of potassium peroxide as an oxygen supply on capsicum, melon and cucumber grown in soilless culture with perlite and rockwool. They found that addition of 1 g L^{-1} of potassium peroxide to the nutrient solution resulted in 20% and 15% increase in the yield of capsicum and melon, respectively, compared to the control (nutrient solution without potassium peroxide). No significant difference was observed in the yield of cucumber.

Comlekcioglu, Gercek & Dikilitas (2008) evaluated fruit yield and yield components of hot pepper grown on a clay soil irrigated by a novel irrigation method called water pillow. Water pillow irrigation is a combination of furrow and drip irrigation and capable of improving water savings, irrigation efficiency, soil protection, and weed control (Gercek 2006). The irrigation treatments were composed of furrow irrigation method (control) with 5-day irrigation intervals, and water pillow irrigation with irrigation intervals of 7, 9, and 11 days. In both irrigation systems, plants were irrigated from one or two sides of the planting rows. The highest fruit yied (41.58 t ha^{-1}) was harvested from $WP_{7\text{-}1s}$ treatment (water pillow, irrigated from one side of the rorws, 7-day irrigation interval). Neither the applied amount of water nor the irrigation frequencies significantly affected the mean fruit weight, length, width, leaves and stem dry and fresh weight of the plants.

The effects of five levels of irrigation irrigation rates consisting of 33, 66, 100, 133, and 166% of crop evapotranspiration (ET) rate on growth parameters and fruit yield of bell peppers were studied (Diaz-Perez 2009). Plants were irrigated by drip tape laterals placed 5 cm below the soil surface with emitters spaced at 20 cm interval and a flow rate of 0.49 L h^{-1} per emitter. The highest fresh weight of fruit yield was observed in plants which were irrigated at 66% ET followed by those which were irrigated at 100, 133, 166, and 33% ET. Plants irrigated at medium rates (66 and 100% ET) were more resistant to chlorosis than the plants which received higher rates of irrigation (133 and 166% ET). Furthermore, plants irrigated at 133 or 166% ET were more susceptible to *Phytophthora capsici* and/or *Pythium* than the plants irrigated at 33 or 66% ET.

Karam et al. (2009) investigated fruit yield and water use efficiency of bell pepper plants under four irrigation treatments receiving 80 (WS1), 60 (WS2), 40 (WS3), and 100% (C) of crop ET. Marketable fruit yield in WS3, WS2, and C treatments were reduced by 38.2, 12.2, and 11.3% compared to the marketable fruit yield in WS1treatment (31.9 t h^{-1}). Moreover, water use efficiency (on a dry weight basis) for WS3, WS2, and WS1 treatment was 39, 35, and 22% higher than water use efficiency for C treatment.

Ismail and Davies (1997) studied the effect of flooding on growth and physiology of young capsicum plants. They found that soil flooding induced early stomatal closure and leaf growth reduction without any reduction in leaf water deficit. Soil water content, soil air-field porosity and gaseous composition determine water and oxygen availability in the soil (Glinski & Lipiec 1990; Russell 1977). At soil moistures above field capacity, root respiration is limited due to insufficient soil aeration, and supply of oxygen to plant roots diminishes (Bergman 1959). Liang, Zhang & Wong (1996) observed a significant correlation between a decrease in soil water content and an increase in soil air-filled porosity.

Water scarcity is an important restriction to agricultural production. Availability of sufficient water and/or poor temporal distribution of rainfall throughout the year are often major restrictive factors in agro-climatic regions. Surface and subsurface drip irrigation (SDI) systems reportedly enhance water use efficiency via reduced soil evaporation and surface runoff, reduced deep percolation of water and pollutants, and enhanced crop yield by providing timely and sufficient nutrients and water for crop plants (Ben-Gal & Lazarovitch 2003).

For the current research, it was hypothesized that aeration of irrigation water supplied at different depths might have a differential effect on growth and yield of the water sensitive crop capsicum. The objectives of this study were to evaluate the effect of different water aeration rates, cross sectional area of emitters (i.e. the air and water flow delivery to the roots) and depth of emitter placement on the plant performance.

5.2 Materials and Methods

5.2.1 Location, Soil and Crop Details

A pot experiment was conducted in the screen-house (67% of full sunlight) on capsicum at the same location as in Chapter 4 in 2007. The capsicum (*Capsicum annuum*) variety Lestat was sown in the nursery on August 3, 2007 and the seedlings were transplanted into white pots 40 cm high and 26 cm in diameter, each lined with a black plastic bag, 43 days after the sowing date.

Each pot was filled with 23 kg of black cracking clay, Vertisol (Australian Soil Classification System as 6AUG-12), whose field capacity, and bulk density were 43 mm H_2O 100 mm^{-1} soil, and 1.3 g cm^{-3}, respectively. A vibrator was used to ensure uniform soil porosity before imposing the treatments. The soil surface was 10 cm below the pot brim. The pot spacing between and within the rows was 70 cm and 60 cm, respectively. Each plot consisted of four pots accommodating eight plants.

5.2.2 Irrigation Set up and Fertigation

Two types of pot drippers were used; Netafim™ PCJ 4 L h^{-1} and Netafim™ PCJ 1.2 L h^{-1} both with 50-400 kPa (7-58 psi) operating pressure range[1].

Irrigation was carried out every other day and the volume of irrigation water for each treatment was calculated based on the soil moisture readings in one pot per plot from a calibrated Micro-Gopher (Soil Moisture Technology Pty Ltd, Australia) capacitance sensor to maintain the soil moisture close to 54 mm H_2O 100 mm^{-1} soil depth. Hence, the irrigation time for each treatment depended on the calculated volume of irrigation water and the emitter water flow rate. Soil moisture readings

[1] The use of product names in this research is not an endorsement of the company's product. These names are mentioned here primarily for the purpose of letting readers know where the relevant materials can be obtained.

were done at 10, 20, and 30 cm below the soil surface prior to irrigation events. The nutrient requirements were supplied as in Chapter 4.

5.2.3 Experimental Design and Treatment Details

The experiment was laid out as a Completely Randomized Block Design with three factors, rate of aeration, depth of emitter placement, and water cross sectional area of the emitters. Aeration was set at three levels consisting of 23%, 12% (air on a volumetric basis), and control i.e. no aeration. Emitters were placed at 5 cm (shallow) and 20 cm (deep) below the soil surface. The cross sectional areas of the emitters were 0.52 mm^2 and 1.25 mm^2 for the 1.2 L h^{-1} and 4 L h^{-1} drippers, respectively. Hence, there were twelve treatment combinations in total. Each treatment was replicated three times.

A short while after the seedlings were transplanted into the pots, signs of collar rot (*Sclerotinia sclerotiorum*) were observed. A systemic fungicide (Fongarid™, active ingredient = 250 g kg^{-1} Furalaxyl) was applied at a rate of 2 g fungicide per 2 L of water. The treatments were imposed from September 26, 2007 (54 days after sowing; DAS).

To obtain a 12% aeration rate, a Mazzei™ air injector model 384 (12.7 mm threads) was used and the pressure at the upstream and the downstream ends of the venturi was maintained at 241 and 69 kPa (35 and 10 psi), respectively. To obtain a 23% aeration rate, a Mazzei™ air injector model 484 (12.7 mm threads) was used with the same pressure differential as model 384. The aeration rates were estimated from a Table provided by the Mazzei™ Injector Company (n.d.) based on the pressure drop across the venturi.

The irrigation layout used for the treatments in this experiment is shown in Figure 5.1. To maintain the required pressure at the inlet of the venturi, the excess water flow before the venturi inlet was returned to the irrigation tank through a bypass. Moreover, the pressure at the venturi outlet was regulated by means of a valve coupled with a pressure gauge fitted on the return pipe to the irrigation tank. The irrigation pumps used in this experiment were 'Onga™' model JSP 100.

In addition to soil moisture, at harvest crop parameters such as the number of fruits, weight of fresh fruit, weight of dry fruit, sampled root length, average diameter of the sampled roots, dry weight of sampled roots, weight of fresh leaves, weight of dry leaves, weight of fresh stems and weight of dry stems per unit area (m^{-2}) were measured. The plants were harvested on December 4, 2007 (123 DAS). Soil respiration rate, light interception, and irrigation water use efficiency (IWUE) for fresh or dry weight of fruits were measured or calculated (for IWUE) occasionally during the growing season.

Soil respiration rate was measured in one pot per plot (totally three measurements per treatment) with an EGM3 gas analyser (PP Systems, UK) and averaged, on November 2, 2007 (91 DAS). Measurements were made immediately after cessation of irrigation.

To determine light interception, photosynthetically active radiation (PAR) above and below the crop canopy was measured with AccuPAR ceptometer (Decagon USA) on November 6, 2007 (95 DAS). Measurements were made between 1100 h and 1400 h. Three readings per treatment were averaged, each consisting of one reading above the canopy and five readings below the canopy by placing the ceptometer at right angles to the crop row. Percent light interception was calculated

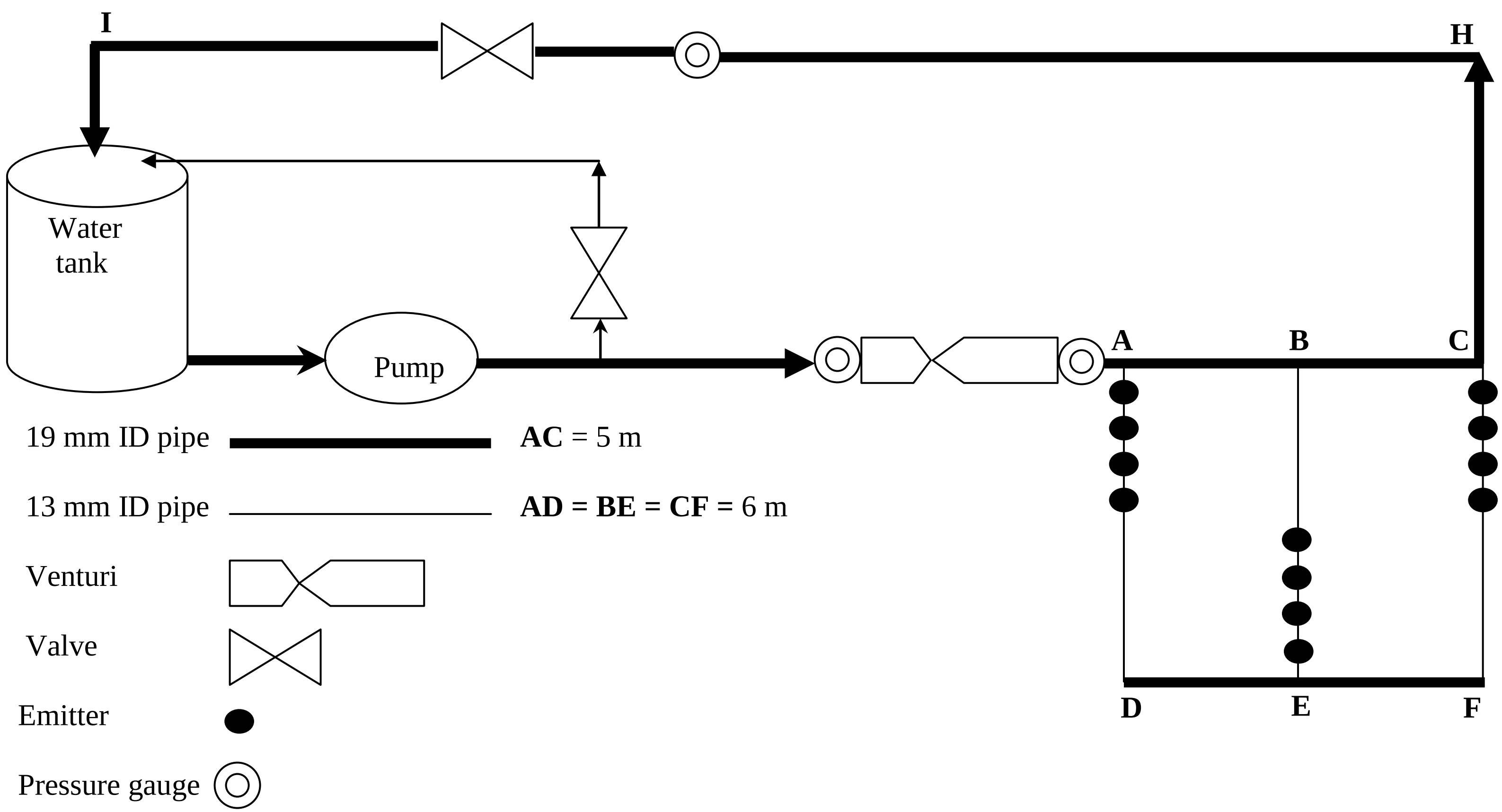

Figure 5. 1 Irrigation layout for the aeration treatments in Chapter 5.

as the difference between PAR above and below the canopy: Light Interception (%) = $[(PAR_{above} - PAR_{below}) / PAR_{above}] \times 100$.

Root samples were obtained from the two centre pots of each plot. This was done by coring with a 4.2 cm diameter soil corer to the entire depth of the pot (one core sample per pot). The core was taken from close to the centre of each pot. The collected core samples were soaked for 24 hours in 1% solution of Ground breaker™ (active constituent 10 g L^{-1} buffered polylignosulfonate) produced by Multicrop (Aust.) Pty. Ltd. Then soil was removed from the roots with a 45 μm sieve following the floatation technique. The living roots were separated manually by discarding the dead ones based on visual observation of the tissue colour. The root length and diameter of the sampled roots were determined using a Hewlett Packard™ scanner and Delta-T software. The washed root samples were placed on transparent trays, using a special mesh panel to hold the roots flat on the base of the root tray. The sample was then scanned into an image file of 'tif' format, which was then passed to Delta-T Scan software for determination of the average diameter and total length of the roots. The imaged root samples were then oven-dried for 48 hours at 70 °C for determination of the dry mass.

For each treatment, the weights of fresh fruits, leaves, and stems of the bordered pots were measured separately and then dried at 70 °C for at least 48 hours until constant weight was reached.

The weight of fresh or dry fruit of each treatment was divided by the corresponding total volume of irrigation water applied to the treatment during the growing season to determine IWUE for the fresh or dry fruits.

The collected data were subject to the general analysis of variance at $P<0.10$ using GenStat version 10.1.

5.3 Results

Neither the aeration levels nor the cross sectional areas of the emitters influenced the soil moisture content of the treatments during the course of the growing season (Figure 5.2). The depth of emitter was the only factor that caused a difference in soil moisture content of the treatments, with deep emitters associated with relatively higher soil moisture in contrast to that equipped with shallow emitters. The average moisture over the soil profile for all the shallow emitter treatments throughout the growing season was almost 5 mm H_2O per 100 mm of soil less than that of all the deep emitter treatments.

Data for the growth parameters, crop yield and yield components are presented in Tables 5.1 and 5.2. All the means were compared at 10% level of confidence. Only the weight of fresh stem (control versus 12% aeration) and IWUE for dry weight of fruits (control versus the aerated treatments) were significantly different between aeration treatments. The control performed better than aerated treatments. A similar trend (caused from the aeration rate) was observed for most of the data presented in Tables 5.1 and 5.2; however, the differences were not significant. Emitter depth was the only main factor that consistently led to significant differences in the growth parameters and the yield components, and in soil respiration. Plants which were irrigated with shallow emitters consistently showed significantly better performance in comparison with those irrigated with deep emitters.

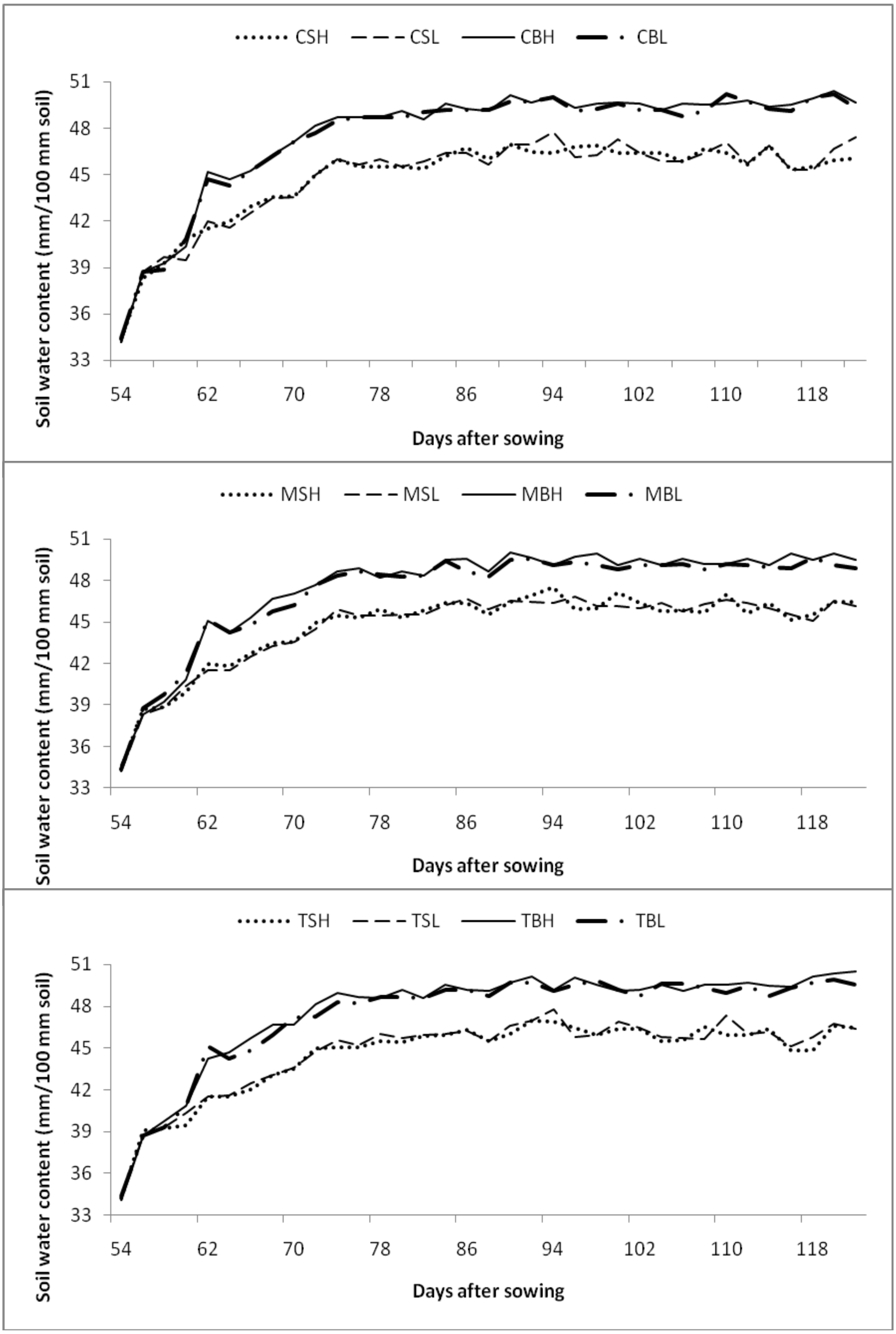

Figure 5. 2 Variation in average soil moisture through the soil profile for the treatments in Chapter 5. The letters C, M, and T, denote 0%, 12%, and 23% aeration, respectively; B and S denote deep and shallow emitter placement, respectively; L and H denote small and large emitter cross sectional area, respectively.

Table 5. 1 Effect of aeration treatments, emitter depth, and water cross sectional area of dripper on soil respiration rate, canopy light interception, the average length, diameter, and weight of sampled roots and the number of capsicum fruit.

Factors	Treatments	Soil respiration rate (g CO_2 m^{-2} h^{-1})	Canopy light interception (%)	Average length root in sample core (mm)	Average root diameter in sample core (mm)	Average root dry weight in sample core (g)	Average number of fruits per m^2
Aeration (A)	0%	0.60	49.5	4229	0.34	0.10	35.90
	12%	0.53	48.8	4778	0.32	0.11	32.50
	23%	0.42	49.8	4324	0.31	0.09	33.50
	LSD[1] (df[2]=22)	**n.s.[3]**	**n.s.**	**n.s.**	**0.03**	**n.s.**	**n.s.**
Emitter water cross sectional area (C)	Large (H)	0.50	49.3	4068	0.32	0.09	32.90
	Small (L)	0.53	49.5	4819	0.32	0.11	35.10
	LSD(df=22)	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
Emitter depth (P)	Shallow (S)	0.61	54.8	5232	0.34	0.13	38.50
	Deep (D)	0.42	43.9	3655	0.31	0.07	29.50
	LSD(df=22)	**0.16**	**3.7**	**938.9**	**0.02**	**0.03**	**3.26**
A×C	0%×H	0.60	49.5	4665	0.34	0.10	35.50
	0%×L	0.59	49.5	3794	0.33	0.09	36.30
	12%×H	0.51	48.5	3771	0.31	0.07	27.60
	12%×L	0.54	49.2	5784	0.33	0.14	37.50
	23%×H	0.40	49.8	3768	0.31	0.08	35.50
	23%×L	0.45	49.8	4879	0.31	0.10	31.60
	LSD(df=22)	**0.28**	**n.s.**	**1626.2**	**n.s.**	**0.06**	**5.65**
A×P	0%×D	0.56	44.0	3967	0.31	0.07	28.97
	0%×S	0.63	55.0	4492	0.36	0.13	42.86
	12%×D	0.33	44.8	4205	0.32	0.07	29.76
	12%×S	0.72	52.8	5350	0.32	0.14	35.32
	23%×D	0.38	43.0	2792	0.29	0.06	29.76
	23%×S	0.47	56.7	5855	0.32	0.13	37.30
	LSD(df=22)	**0.28**	**6.4**	**1626.2**	**0.04**	**0.06**	**5.65**
C×P	H×D	0.33	44.1	3582	0.32	0.07	28.44
	H×S	0.67	54.4	4554	0.32	0.10	37.30
	L×D	0.51	43.8	3727	0.30	0.06	30.56
	L×S	0.54	55.2	5911	0.35	0.16	39.68
	LSD(df=22)	**0.23**	**5.3**	**1327.8**	**0.03**	**0.05**	**4.61**
A×C×P	0%×H×D	0.46	43.7	3708	0.33	0.08	28.17
	0%×H×S	0.74	55.3	5622	0.36	0.13	42.86
	0%×L×D	0.65	44.3	4226	0.29	0.07	29.76
	0%×L×S	0.53	54.7	3362	0.37	0.12	42.86
	12%×H×D	0.27	45.7	3953	0.32	0.07	26.19
	12%×H×S	0.75	51.3	3590	0.30	0.08	28.97
	12%×L×D	0.39	44.0	4457	0.32	0.08	33.33
	12%×L×S	0.70	54.3	7111	0.35	0.21	41.67
	23%×H×D	0.26	43.0	3085	0.31	0.07	30.95
	23%×H×S	0.53	56.7	4451	0.31	0.09	40.08
	23%×L×D	0.49	43.0	2499	0.28	0.04	28.57
	23%×L×S	0.40	56.7	7259	0.34	0.17	34.52
	LSD(df=22)	**0.40**	**9.1**	**2299.8**	**0.05**	**0.08**	**7.99**

[1]LSD = Least Significance Difference between two means. [2]df = degrees of freedom.
[3] n.s. = not significant.

Table 5. 2 Effect of aeration treatments, emitter depth, and water cross sectional area of emitter on fresh and dry weights of fruit, leaf and stem for capsicum.

Factors	Treatments	Fresh weight of fruit (g m^{-2})	Dry weight of fruit (g m^{-2})	Fresh weight of leaf (g m^{-2})	Dry weight of leaf (g m^{-2})	Fresh weight of stem (g m^{-2})	Dry weight of stem (g m^{-2})	IWUE fresh weight of fruit (g L^{-1})	IWUE dry weight of fruit (g L^{-1})
Aeration (A)	0%	4207	368.2	431	89.2	479	117.6	5.65	0.494
	12%	4000	341.8	393	99.3	414	112.1	5.34	0.455
	23%	3969	357.3	373	90.3	415	109.4	5.32	0.481
	LSD(df=22)	**n.s.**	**22.4**	**n.s.**	**n.s.**	**49.0**	**n.s.**	**n.s.**	**0.030**
Emitter water cross sectional area (C)	Large (H)	3985	351.5	416	94.6	432	110.0	5.37	0.475
	Small (L)	4132	360.0	382	91.3	440	116.1	5.50	0.479
	LSD(df=22)	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
Emitter depth (P)	Shallow (S)	5027	438.8	504	115.4	570	148.0	5.82	0.508
	Deep (D)	3091	272.7	294	70.4	302	78.0	5.05	0.446
	LSD(df=22)	**204.8**	**18.3**	**54.4**	**9.3**	**40.0**	**11.5**	**0.30**	**0.025**
A×C	0%×H	4361	376.7	472	95.9	501	124.6	5.70	0.498
	0%×L	4053	359.6	391	82.4	456	110.7	5.55	0.490
	12%×H	3588	304.5	351	92.9	353	97.1	4.90	0.416
	12%×L	4412	379.0	535	105.8	475	127.1	5.75	0.494
	23%×H	4007	373.2	426	94.9	441	108.3	5.40	0.510
	23%×L	3932	341.4	319	85.7	389	110.5	5.20	0.453
	LSD(df=22)	**354.7**	**31.7**	**94.3**	**16.1**	**69.3**	**20.0**	**0.52**	**0.043**
A×P	0%×D	3020	263.5	281	64.9	292	77.6	4.98	0.435
	0%×S	5393	472.8	581	113.5	665	157.7	6.31	0.553
	12%×D	3156	266.3	267	78.2	290	82.8	5.09	0.429
	12%×S	4845	417.2	519	120.5	538	141.4	5.59	0.481
	23%×D	3096	288.2	333	68.1	324	73.6	5.08	0.473
	23%×S	4842	426.4	412	112.4	506	145.1	5.57	0.490
	LSD(df=22)	**354.7**	**31.7**	**94.3**	**16.1**	**69.3**	**20.0**	**0.52**	**0.043**
C×P	H×D	3032	272.1	317	72.0	308	78.9	5.03	0.451
	H×S	4938	430.9	516	117.1	556	141.0	5.71	0.498
	L×D	3149	273.3	271	68.8	297	77.1	5.07	0.440
	L×S	5115	446.7	492	113.8	583	155.1	5.93	0.518
	LSD(df=22)	**289.6**	**25.9**	**77.0**	**13.1**	**56.6**	**16.3**	**0.42**	**0.035**
A×C×P	0%×H×D	2604	232.6	282	65.3	271	76.9	4.35	0.388
	0%×H×S	6117	520.9	661	126.6	732	172.3	7.14	0.608
	0%×L×D	3437	294.4	281	64.5	313	78.3	5.62	0.481
	0%×L×S	4670	424.7	501	100.3	598	143.1	5.49	0.499
	12%×H×D	3171	263.5	269	78.0	293	84.9	5.20	0.432
	12%×H×S	4006	245.5	432	107.7	414	109.3	4.64	0.400
	12%×L×D	3141	269.2	265	78.4	287	80.7	4.97	0.426
	12%×L×S	5683	488.8	606	133.2	663	173.5	6.54	0.563
	23%×H×D	3322	320.2	399	72.8	358	75.0	5.52	0.533
	23%×H×S	4691	426.3	454	117	524	141.5	5.36	0.487
	23%×L×D	2870	256.2	268	63.5	289	72.3	4.63	0.413
	23%×L×S	4993	426.5	370	107.8	489	148.7	5.77	0.493
	LSD(df=22)	**501.6**	**44.9**	**133.4**	**22.7**	**98.1**	**28.2**	**0.73**	**0.061**

Although the cross sectional areas of the emitters had no significant effect on the yield and growth parameters, it appears that the plants which were irrigated with emitters of small cross sectional area performed slightly better than those irrigated with emitters of large cross sectional area. In some cases, interactions among the main factors led to significant effects on the yield or growth parameters. From Table 5.1, the diameter and dry weight of the sampled roots showed a significant difference owing to the interaction between the emitter cross sectional area and emitter depth, whereas the sampled root length was influenced significantly by the interaction among the three main factors. Also as seen in Table 5.2, none of the yield components were significantly affected from the interaction between the emitter cross sectional area and the emitter depth, whereas other combinations of interaction between/among the main factors significantly influenced the yield components.

After harvest, the emitters were removed from the soil to measure the air flow rate from the emitters. The same pressures, as those during the growing period, were maintained at the inlet and outlet of the venturi as well as within the return pipe (Figure 5.1) for all the aeration treatments. There was no sign of air bubble delivery from the emitters in any of the aeration treatments. It was revealed that all the air supplied by the venturi flowed straight through the manifold ABC and directly entered into the return pipe CHI without going into any of the laterals (Figure 5.1); suggesting a preferential flow of air bubbles.

5.4 Discussion

The piping layout used in the experiment resulted in the by-passing of the air bubbles through the return pipe. Air bubbles take the route with the least resistance, which will lead to the least loss of head. Head loss (h_L) in a pipe is given by the Darcy-Weisbach formula as:

$$h_L = f \times \frac{L}{d} \times \frac{V^2}{2g} \tag{5.1}$$

where, f, L, d, V, and g are friction factor, pipe length, pipe internal diameter, average velocity, and the gravity acceleration, respectively. The continuity equation:

$$Q = A \times V \tag{5.2}$$

links V with Q and A which are volume flow rate, and pipe cross sectional area, respectively. Combining (5.1) and (5.2) gives:

$$h_L = f \times \frac{L}{d^5} \times \frac{8Q^2}{g\pi^2} \tag{5.3}$$

From (5.3), it is evident that head loss in a circular pipe is inversely proportional to the 5th power of the pipe internal diameter. Hence, a very small reduction in the pipe diameter will lead to a huge rise in the head loss. Therefore, the air bubbles preferred to flow through the 19 mm ID pipes ABC and CHI (Figure 5.1) rather than entering into the 13 mm ID pipes AD, BE, and CF.

As the air bubbles by-passed the laterals and flowed straight into the return pipe, the differing cross sectional areas of the emitters would not have any effect on the delivery of the air bubbles to the plant roots. It follows that from the oxygation aspect, neither the aeration levels (except for stem fresh weight as in Table 5.2) nor the cross sectional areas of the emitters would be expected to influence crop performance. In other words, depth of emitter placement was the only factor affecting the growth parameters, crop yield and yield components. Hence, the experimental treatments are reduced to the comparison between ‘shallow’ and ‘deep’ emitters.

The relatively lower soil moisture in the shallow treatment in comparison with the deep treatment (Figures 5.3 and 5.4) is mainly attributed to the higher soil evaporation in the shallow treatment. Subsurface drip irrigation is defined as delivery of water beneath the soil surface through drippers, with water flow rates usually in the same range as surface drip irrigation (Singh & Rajput 2007). Since in subsurface drip irrigation method the soil surface remains dry, the unsaturated hydraulic conductivity of the topsoil becomes very small and consequently evaporation from soil surface would be greatly reduced (Thompson, Huan-cheng & Yu-yi 2009). In the shallow treatment, the emitters were sufficiently close to the soil surface to allow for evaporation of moisture from the soil surface. It follows that in the shallow treatment, in addition to the water uptake by the roots, part of the irrigation water was lost through soil evaporation.

To explain the noted effect of emitter depth on the growth parameters, the difference in the soil water content of the treatments and its influence on the soil air and relative gas diffusivity are analyzed. According to Bresler (1977), Schwartzman and Zur (1986), and Zur (1996), water movement from a point source through a soil profile is three dimensional. As water starts flowing from a single dripper into an unsaturated soil, a wetting front is formed and advances radially within the soil. The soil water content behind the wetting front increases as irrigation continues. Figures 5.3 and 5.4 present soil moisture variations throughout the soil profile at depths 10, 20, and 30 cm over the growing season. The soil moisture at the shallow depth did not differ between depths of emitters, for the measurement was made just prior to irrigation when the surface had dried out. Approximately two weeks after imposition of the treatments (i.e. 64 days after sowing), soil moisture within the bottom 20 cm of the soil profile in both treatments exceeded the field capacity (i.e. > 43 mm H_2O

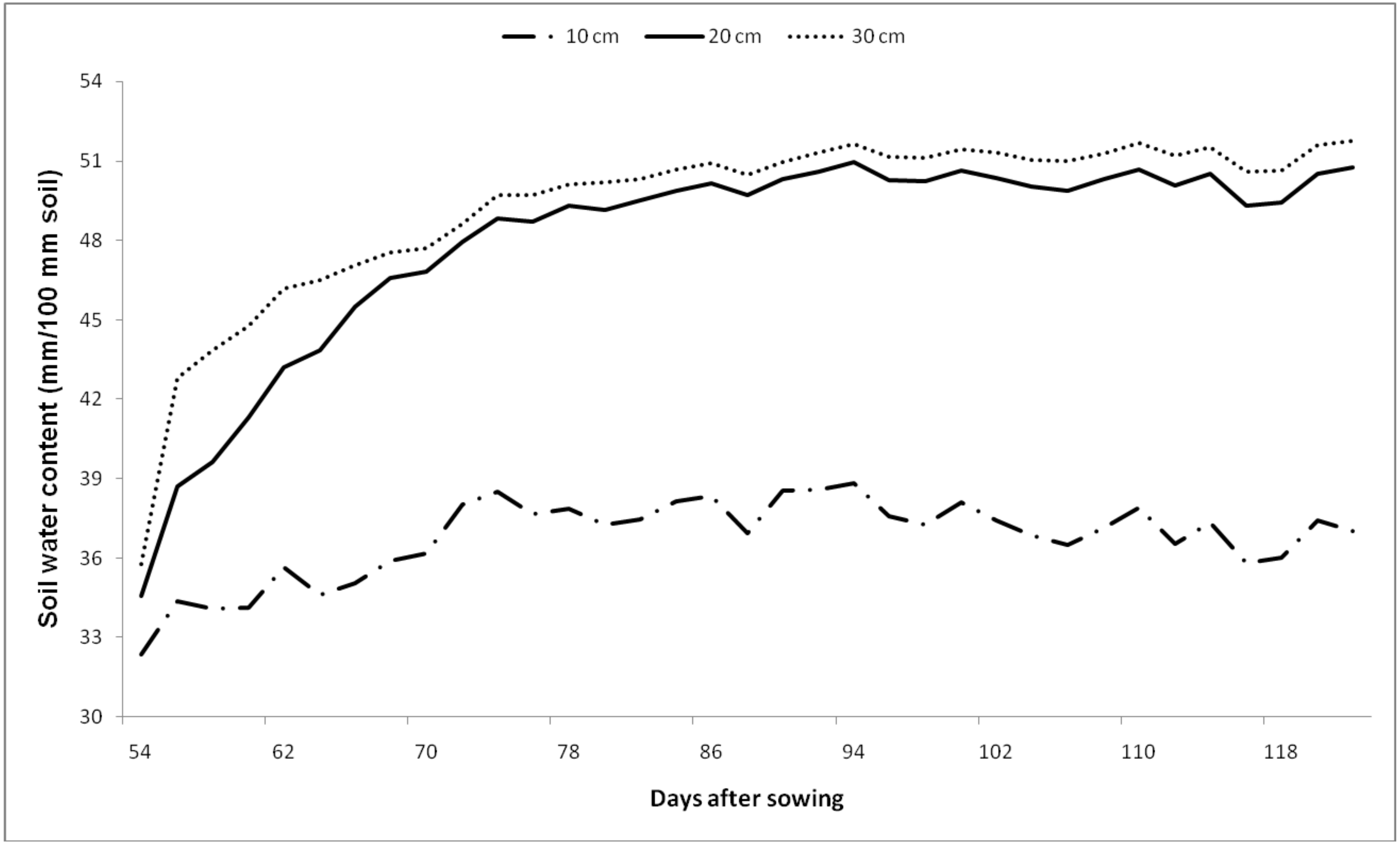

Figure 5. 3 Soil moisture variation in the 'shallow emitter' treatment.

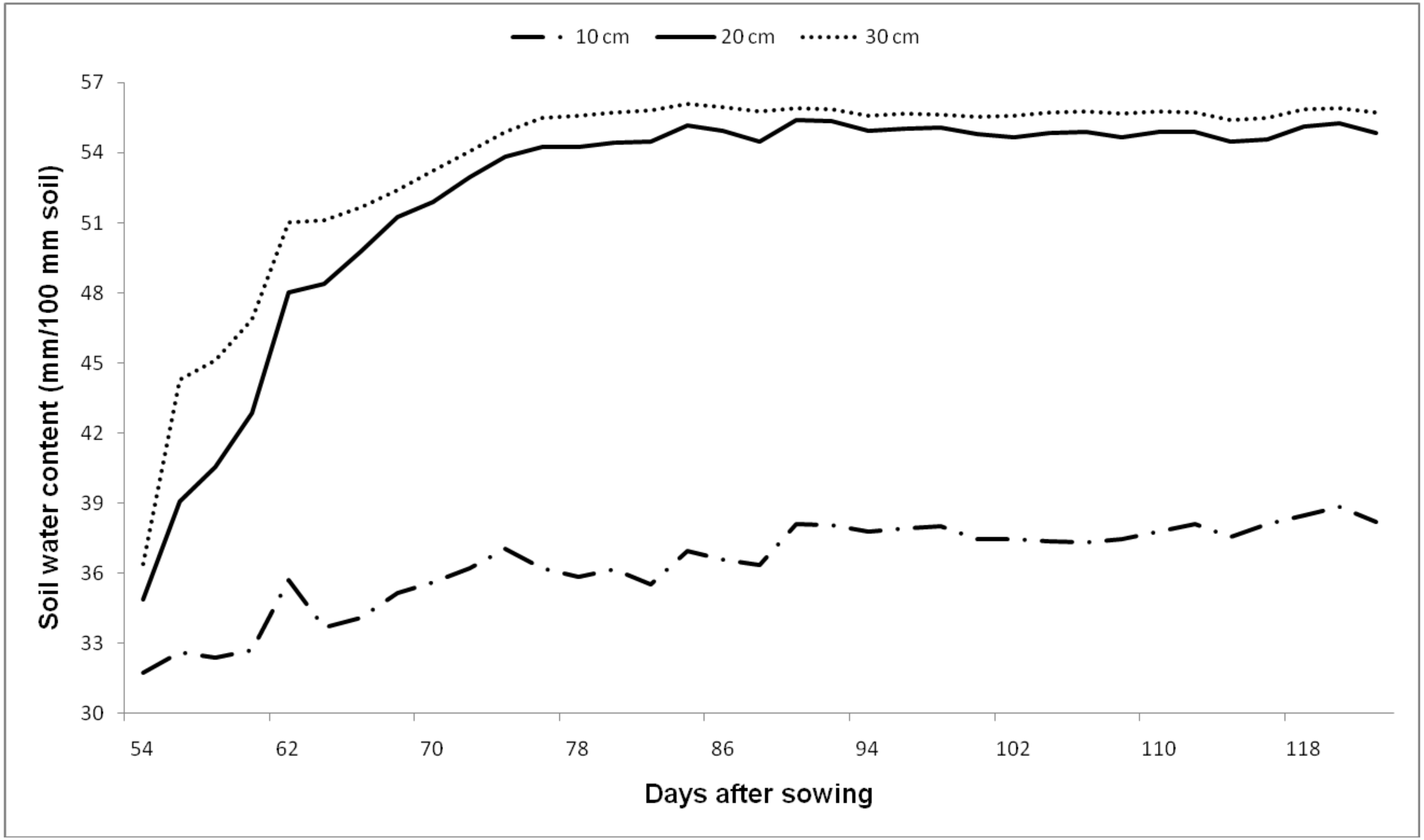

Figure 5. 4 Soil moisture variation in the 'deep emitter' treatment.

100 mm^{-1} soil). At soil moisture above the field capacity, respiration of plant roots is limited because of insufficient soil air content, and supply of oxygen to roots diminishes (Bergman 1959). The capacity of soil for oxygen supply is expressed by relative gas diffusivity estimated by dividing coefficient of gas diffusion in soil by the coefficient of gas diffusion in air (Grable & Siemer 1968; Osozawa, Kozai & Kubota 1990). Moldrup et al. (2000) developed a simple and conceptual model for the prediction of relative gas diffusivity in repacked soil:

$$\frac{D_P}{D_0} = \frac{\varepsilon^{2.5}}{\Phi} \tag{5.4}$$

where, D_p is the coefficient of gas diffusion in soil (cm^3 soil air cm^{-1} soil sec^{-1}), D_0 is the coefficient of gas diffusion in free air (cm^2 air sec^{-1}), ε is the air-filled porosity of soil (cm^3 soil air cm^{-3} soil) and Φ is the total porosity of soil (cm^3 cm^{-3}). Equation (5.4) was used to calculate relative gas diffusivity for the shallow and deep treatments over the growing period. Assuming a soil particle density (ρ_s) of 2.65 g cm^{-3} for the black cracking clay soil (Vertisol) used in this experiment, the soil total porosity and soil air-filled porosity were respectively calculated:

$$\Phi = 1 - \frac{\rho_b}{\rho_s} \tag{5.5}$$

$$\varepsilon = \Phi - \theta_i \tag{5.6}$$

where, ρ_b is the soil bulk density (1.3 g cm^{-3}) and θ_i is the average soil water content (over the soil profile) on the *i*th DAS.

Figure 5.5 presents the variation in the season-long calculated relative gas diffusivity (RGD) for the shallow and deep treatments. On a relative basis, the calculated RGD values for the deep treatment were smaller than those for the shallow

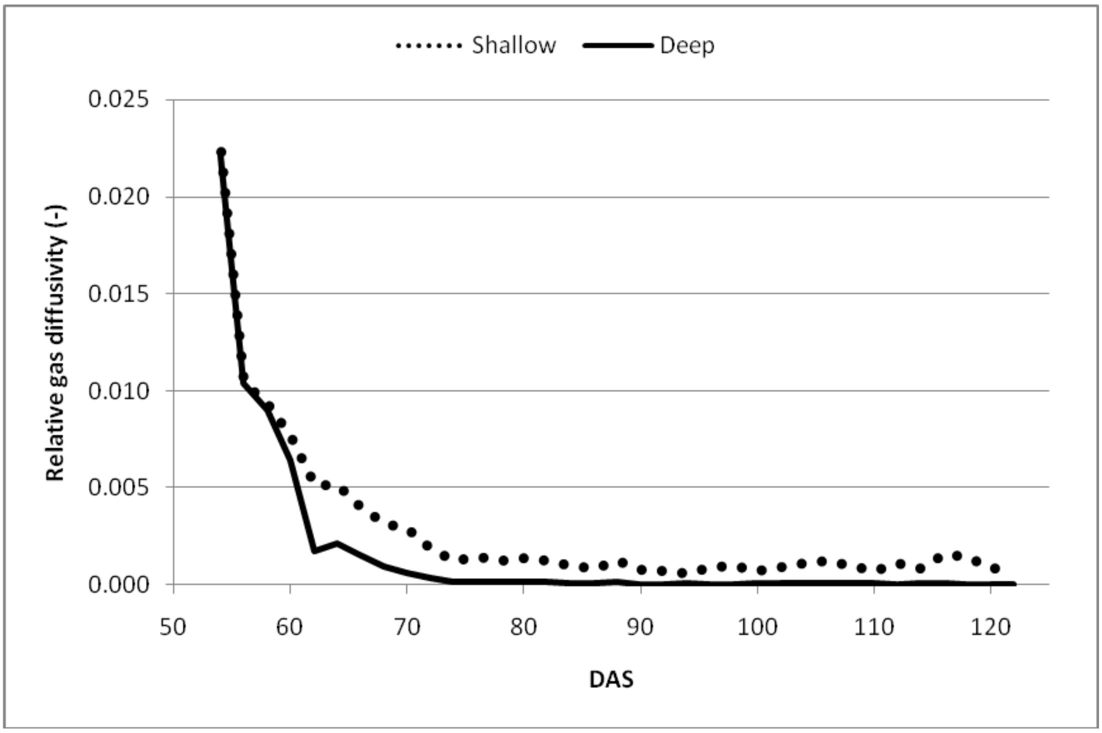

Figure 5. 5 Season-long variation in calculated relative gas diffusivity for the shallow and deep treatments.

treatment. It follows that oxygen diffusion to the root zone of the plants in the deep treatment was more restricted and hence root respiration in this treatment would be poorer in comparison with the shallow treatment, as noted in Table 5.1. Fernhout and Kurtz (2002) showed that insufficient root respiration leads to reduction in nutrients and water uptake, and alterations in soil chemistry yield toxic compounds that restrict the general growth of plants. Furthermore, Tan et al. (2009) conducted a 3-year study to explore the effect of subsurface and surface drip irrigation, and broadcast fertilizer or fertigation, on tomato grown on two types of soil: clay loam and loamy sand. They found that on the light textured soil, average yields of marketable tomato were enhanced by 35 to 37% under the surface drip-broadcast fertilizer and surface fertigated treatments relative to the non-irrigated control treatments, whereas under subsurface-fertigated and subsurface-broadcast treatments average marketable yield of tomato was enhanced by 43 to 47% relative to non-irrigated treatments. On the fine textured soil, average yields of marketable tomato were enhanced by 26 to 35% under surface drip-fertigated and surface-broadcast treatments relative to non-irrigated treatments, whereas under subsurface-fertigated and subsurface broadcast treatments average yield of tomato was enhanced by 14 to 25% compared to non-irrigated treatments. It follows that in the light textured soil with generally high RGD (Kawamoto et al. 2006); the average increase in tomato yield for the subsurface drip treatments was 9% higher than the average increase in tomato yield in the surface treatments. The improved performance of plants irrigated by subsurface drip irrigation is likely due to enhanced access to water and nutrients compared to the surface drip irrigation. In contrast to the light textured soil, on the heavy textured soil the average tomato yield in the subsurface drip treatments was 11% less than the average tomato yield in the surface drip treatments. It is shown that under subsurface drip irrigation, a saturated front is maintained in the vicinity of the dripper as water discharged from each dripper advances slowly in all directions and the gravitational force is not very noticeable, especially in fine textured soils (Bresler 1977). Hence, it is likely that on heavy textured soil, when the infiltrated rates of irrigation water are close to, or exceed, the evapotranspiration rate, crops irrigated with subsurface drip irrigation could suffer from hypoxia and accordingly root growth and crop yield will be reduced (Camp 1998). The above-mentioned reasons justify the better performance of the plants in the shallow treatment compared to those in the deep treatment.

5.5 Conclusion

The depth of emitters consistently showed a significant effect on the yield and growth parameters of capsicum. Availability of more moisture in the soil surface of the shallow treatments during and a while after cessasion of irrigation, most likely led to larger unsaturated soil hydraulic conductivity and consequently larger water depletion from the soil profile in comparison with the deep treatments. Owing to the higher soil water content in the deep emitter treatment compared to the shallow one, the calculated RGD in the deep treatments was always less than that in the shallow treatment. Hence, the relatively enhanced gas exchange in the root zone of the shallow treatment led to better crop performance in comparison with the deep treatment.

The emitter cross sectional area had no significant influence on the yield and yield components of capsicum. However, the low flow rate emitters generally performed better than the high water flow rate ones. Possibly, the faster increase in the soil water content followed by accordingly lower RGD in the treatments irrigated with high flow rate emitters might have led to poorer soil respiration and crop performance compared to the treatments irrigated with low flow rate emitters.

It was clearly shown that preferential flow of air bubbles will result in failure of rhizosphere aeration when a piping layout such as in this experiment, is employed. Great care is needed to maintain appropriate hydraulic conditions for all pipe branches in terms of resistance to water flow in order to avoid preferential flow of air bubbles into the branch with the least resistance to water flow. It may be close to impossible to provide such conditions for a branching pipe system. Substituting a branching pipe system with a single pipe with returns in alternate rows of pots together with appropriate type and concentration of surfactant, to improve the distribution of air flow rates along the lateral pipe, might be solutions to this issue.

In conclusion, although neither the 12% nor the 23% aeration rate was supplied to the aeration treatments, the concept of relative gas diffusivity was employed as a measure of soil oxygen status to show the crucial effect of soil aeration on the plant performance across the treatments.

Chapter 6: Response of four vegetable species to oxygation

ABSTRACT

A pot experiment was conducted in a screen-house to assess the response of four vegetable species of different rooting morphology consisting of pak choi and spring onion (fibrous root), beetroot (modified taproot), and dwarf bean (taproot) to root zone aeration. Aeration of irrigation water was accomplished by mixing air at the rate of 19% by volume via an air injector venturi. A recirculating drip irrigation system with single lateral pipe and asymmetric connectors resulted in efficiency of air bubble delivery of 93% for all the aerated treatments. For spring onion, soil respiration rate, maximum leaf length, and fresh weight of leaf, stem, and bulb were significantly increased by the oxygation treatment; however no effect was seen with the other species. This lack of response is ascribed to a relatively higher sensitivity of spring onion to waterlogging, and to inefficiencies in air delivery along the length of the irrigation lines, with air delivery declining with distance along the pipe. Indeed, the pots in the first block of all the aerated treatments, which received 8 L h^{-1} air flow, demonstrated markedly enhanced crop yield in comparison with the control in all the species. Latter blocks, which received only 3-5 L h^{-1} air per pot, showed no growth response. It was noteworthy that delivery of 8 L h^{-1} per pot air flow to the first block of all the aerated treatments markedly enhanced crop yield in comparison with the control in all the species. Moreover, the remarkably high air flow rates from the emitters in the first block of all the aerated treatments, which were closer to the air injector venturi, caused 42% reduction in the water flow rate of those emitters.

6.1 Introduction

Drip irrigation is described as delivery of small quantities of water from small diameter low density polyethylene pipes via outlets called emitters. This is the main advantage of drip over other irrigation methods and makes it possible to maintain relatively high water content and available nutrient concentrations within the root zone (Rawlins & Raats 1975). The system is mostly used in orchards and vineyards, but also is used for vegetables, ornamentals, and for landscape plantings.

Kumar, Imtiyaz & Kumar (2009) studied the possibility of using drip irrigation and microsprinkler systems for production of vegetables in a canal command area. These irrigation methods were compared with the existing flood irrigation system for production of onion. The onion performance was the highest under microsprinkler irrigation system, followed by drip and the lowest was achieved by flood irrigation. The enhanced yield of onion obtained from microsprinkler irrigation system was attributed to creation of a favourable microclimate and enhancement in aeration of the rhizosphere. Similar improvement in the yield of kiwi fruit crops due to better soil aeration in the root zone under microjet irrigation system in comparison with drip irrigation was reported by Holzapfel et al. (2000).

Green bean response to conventional SDI and partial root zone drying (PRD) via alternating subsurface drip irrigation in a sandy clay soil was studied by Gencoglan, Altunbey & Gencoglan (2006). The irrigation treatments did not significantly affect dry weight of biomass and green bean yield; however, the PRD irrigation treatment resulted in 16% higher overall irrigation water saving compared with the SDI treatment. Possibly, the enhanced root zone aeration under the PRD irrigation technique improved root respiration as well as water and nutrient uptake and offset the relative reduction in crop yield in comparison with conventional SDI.

A sufficient supply of oxygen to the rhizosphere is completely necessary for optimal maintenance and root growth, prevention of root-borne diseases, and enhanced nutrient uptake. Lack of sufficient oxygen in the rhizosphere may result in inferior shoot and root performance and a rise in the disease incidence, such as *Phytophthora* and *Pythium* (Cherif, Tirilly & Belanger 1997). Aerated subsurface drip irrigation (SDI) is capable of alleviating the soil hypoxia/anoxia by providing air to the oxygen-depleted plant root zone. This could be achieved by coupling air injector venturi(s) to suck air into the subsurface drip irrigation system (Goorahoo et al. 2002). It has been shown that aeration of irrigation water via air injector venturi (referred to as oxygation or AirJection Irrigation) significantly enhanced yield and growth of several crop species including vegetable soybean (Bhattarai, Huber & Midmore 2004), tomato (Bhattarai, Pendergast & Midmore 2006), and chickpea (Bhattarai, Midmore & Pendergast 2008).

In the previous chapters (Chapters 4 and 5), it was shown how certain branching pipe systems and use of symmetric connectors in the oxygation of grain sorghum and capsicum led to failure or ineffective root zone aeration. The objective of this research was to assess the response of four vegetable species of different rooting systems to oxygation via air injector venturi using single lateral pipes and asymmetric connectors. The vegetables were two fibrous root species pak choi (*Brassica rapa* var. Chinensis) and spring onion (*Allium* spp.) and two taproot species bean (*Phaseolus vulgaris* L.) and beetroot (*Beta vulgaris* L.).

6.2 Materials and Methods

A pot experiment was conducted in the screen house (67% of full sunlight) on four vegetable species - pak choi variety Green, dwarf bean variety Brown Beauty, spring onion variety Evergreen Bunching, and beetroot variety Early Wonder - at the same location as in Chapter 4 from April 2008 until August 2008. The experiment was laid out as a Completely Randomised Block Design (CRBD) with each species replicated four times with two treatments, irrigation with aerated water or non-aerated water (control). The total length and width of each block were 2.1 m and 1.8 m, respectively. In each block, all the treatments consisted of four 21 L containers, each accommodating three, five, nine, and three plants per experimental plot for pak choi, beetroot, spring onion and bean, respectively. Each container was of 40 cm height and 26 cm diameter and filled with 28 kg of black cracking clay soil classified as a Vertisol (Australian Soil Classification System as 6AUG-12), whose field capacity and bulk density were 43 mm H_2O 100 mm^{-1} soil, and 1.3 g cm^{-3}, respectively. The containers were spaced 30 cm within rows and 60 cm between rows. The nutrient requirements were supplied as in Chapter 4.

For each aeration treatment, air was injected into the subsurface drip irrigation system by means of a Netafim™ venturi[1] model F¾-0.9. The inlet and outlet pressures at the venturi were maintained at 269 and 83 kPa (39 and 12 psi), respectively. The rate of aeration defined as the ratio of total air flow rate supplied by the venturi (for the set pressure differentials) to total water flow rate was directly measured at the return to the irrigation tank. To measure the air or water flow rate, all

[1] The use of product names in this research is not an endorsement of the company's product. These names are mentioned here primarily for the purpose of letting readers know where the relevant materials can be obtained.

the emitters on the irrigation pipe were shut so that the entire air or water flowed back to the tank via the lateral pipe. Using a measuring jug and a stopwatch, the water volume collected in the jug for about 17 seconds was measured. To collect air bubbles, the jug was inverted and immersed into the tank, and the return pipe was put into the immersed jug. Water inside the jug was replaced by air bubbles. After about 83 seconds the pipe was removed from the jug and the volume of the air accumulated in the inverted measuring jug was recorded. This procedure was repeated five times for measurement of air and water flow rates and then averaged. The average aeration rate for all the aerated treatments was 19% air by water volume. There was one venturi for each species by oxygation combination. The pot drippers used in this experiment were Netafim™ PCJ 1.2 L h^{-1} with 50-400 kPa (7 and 58 psi) operating pressure. The drippers were placed 15 cm below the soil surface, one per centre of each pot. Asymmetric connectors attached to 4 mm riser tubes connected the emitters to the lateral pipes. Seeds were sown on April 10, 2008 and the treatments were imposed 42 days after sowing (DAS).

Instead of using a branching pipe system, a single 19 mm internal diameter (ID) polyethylene pipe was used for every treatment to prevent any preferential flow of air bubbles in the aeration treatments (Figure 6.1). Asymmetric connectors similar to those described in sub-section 3.2.1.1 in Chapter 3 were used for the drippers. Water pressure at the end of each irrigation pipe (before entering into the water tank) was maintained at 76 kPa (11 psi) by means of a valve.

Soil moisture was measured for all the treatments every other day in one pot per experimental plot by means of a calibrated Micro Gopher™ (Soil Moisture Technology Pty Ltd, Australia) capacitance sensor. Irrigation was scheduled to maintain the moisture of the soil profile at field capacity (i.e. 43 mm H_2O per 100

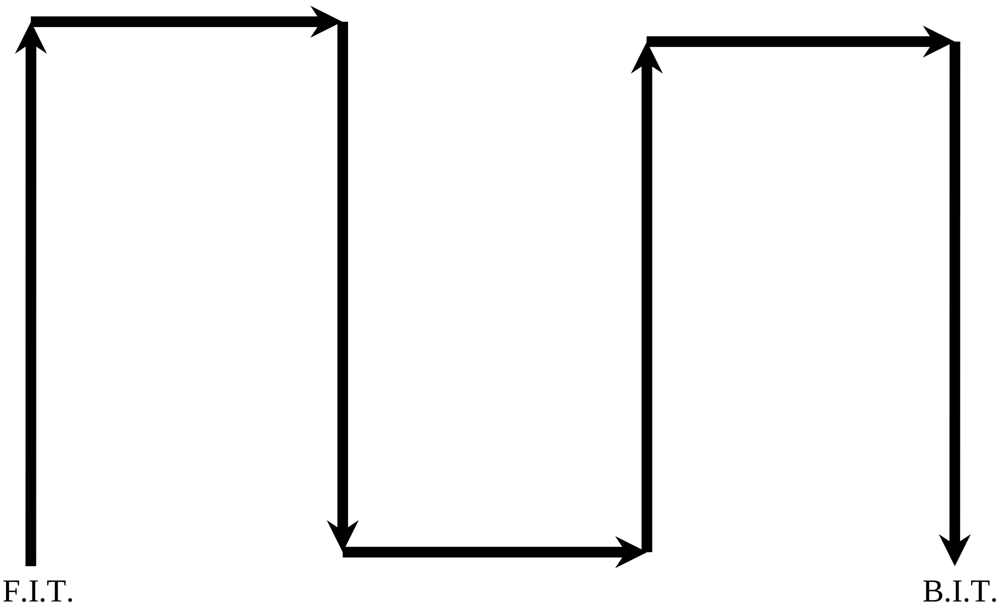

Figure 6. 1 Irrigation layout with a single lateral pipe. The letters F.I.T. and B.I.T. stand for ‘From Irrigation Tank’ and ‘Back to the Irrigation Tank’, respectively. The arrows show the direction of flow.

mm soil) in all the treatments. The irrigation interval was every other day.

Oxygen concentration in the soil was measured using PSt3 oxygen-sensitive fibre optic mini-sensors with a Fibox-3 oxygen meter (PreSens GmbH, Germany). It is an optical sensor that measures the oxygen concentration in the gaseous and liquid phase. The sensors were placed in the pots at 15 cm depth, 10 cm away from the emitter.

During the growing season, SPAD readings (for all species), soil respiration rate (for pak choi and spring onion), leaf photosynthetic rate, transpiration rate, instantaneous water use efficiency (calculated as the ratio of leaf transpiration rate to leaf photosynthetic rate), and stomatal conductance (for pak choi only and at the same time) were measured. The leaf gas exchange parameters were measured with an infrared gas analyser (IRGA) model LGA-4 (ADC UK) on three youngest fully expanded exposed leaves per pot between 1400-1500 h on July 2, 2008 (i.e. 82

DAS). In each block, the two inner pots of the treatments were used for measurements.

SPAD readings (a surrogate for leaf chlorophyll concentration using a Minolta chlorophyll meter SPAD-502) for pak choi, bean, spring onion, and beetroot were done 82 DAS, 73 DAS, 104 DAS, and 73 DAS, respectively. For all treatments, two pots (the inner pots) in each block were selected. In each pot, one fully expanded uppermost leaf per plant was measured and the average of the readings for the pot was used in the statistical analyses.

Soil respiration rate for pak choi and spring onion was measured with an Environmental Gas Monitoring apparatus (EGM-3 from PP Systems, UK) on 82 and 81 DAS, respectively. For both species, soil respiration rate was measured one hour after cessation of irrigation.

To illustrate the effect of soil water content, soil air-filled porosity and aerated water on the balance of available soil oxygen for root respiration, a simple calculation was performed for each treatment as follows:

1. Total soil porosity (Φ), assuming clay soil particle density (ρ_s) of 2.65 g $cm^{-3}$and clay soil bulk density (ρ_b) of 1.3 g cm^{-3}:

   $$\Phi = 1 - \frac{\rho_b}{\rho_s} = 1 - \frac{1.3}{2.65} = 0.51$$

2. Volume of soil (V_s) in a cylindrical pot with a diameter 26 cm and height of 40 cm: V_s = 0.21 L

3. Season-long average soil water content (θ) before irrigation for each treatment (from Figure 6.2).

4. Volume of water (V_w) delivered to each pot to achieve FC:

   $V_w = (0.43 - \theta) \times V_s$, in L

5. Soil air-filled porosity (ε) at the end of an irrigation event:

   $\varepsilon = \Phi - 0.43 = 0.51 - 0.43 = 0.08$

6. Air density (ρ_a) at 25 °C: ρ_a = 1.18 mg cm^{-3}

7. Oxygen content of atmospheric air 0.2095

8. Maximum amount of oxygen (O_s) in the air-filled soil pores of a pot, remaining at the end of an irrigation event:

   $O_s = \varepsilon \times V_s \times \rho_a \times 0.2095$, in mg. = 0.08 × 0.21 × 1.18 × 0.2095 = 0.0042

9. Average oxygen concentration (O_t) in fresh water at equilibrium with atmospheric oxygen based on measurements: 7 mg L^{-1}

10. Total oxygen available (O_c) for a pot in a control treatment, at the end of an irrigation event: $O_c = O_s + (O_t \times V_w)$, in mg

11. Average air volume (A_e) delivered to a pot supplied via oxygation, in cm^3 s^{-1})

12. Oxygation time (t), based on 1.2 L h^{-1} emitter water flow rate:

    $t = \left(\frac{V_w}{1.2}\right) \times 3600$, in s

13. Amount of oxygen (O_e) delivered to a pot via oxygation:

    $O_e = A_e \times t \times \rho_a \times 0.2095$, in mg

14. Total oxygen available (O_a) for a pot in an aerated treatment:

    $O_a = O_e + O_s + (O_t \times V_w)$, in mg

Pak choi, beetroot, spring onion, and bean were harvested 91, 108, 122, and 116 DAS, respectively. After harvest, air flow rate from emitters, yield and yield components including leaf count, pod count, fresh weight of leaves, stems, roots, length of the longest leaf per pot, the maximum diameter of the beetroot, and Brix were measured. For determination of Brix, a plug (5-7 g) was taken equatorially using a corer (27 mm diameter, 10 mm deep). Beetroot juice was extracted from the flesh tissue sample by means of a garlic press, and Brix was determined using a temperature compensated refractometer (Bellingham and Stanley RMF 320, UK). Dry matter data on leaf, stem, and pod were obtained for bean after the components were dried for 48 h at 70 ºC.

The emitter air flow rates and efficiency of air bubble delivery for the aerated treatments were measured by the method described in Chapter 3. In addition to measurement of emitter air flow rates for all the oxygated species, water flow rate from emitters were measured for the oxygated spring onions. The water flow rate measurements were done for two cases: (a) while water alone was discharged from the emitters, and (b) while water and air were discharged. For each species, the collected data were analysed with t-test at $P<0.10$. Also, a general analysis of variance was performed on the SPAD readings of all the species at $P<0.10$ using GenStat version 10.1.

6.3 Results

6.3.1 Soil water content, emitter air flow rates, and estimated total available oxygen for all treatments

For all treatments, the average soil moisture over the soil profile was similar throughout the growing period, varying between 39 and 40 mm H_2O 100 mm^{-1} soil (Figure 6.2). However, the soil water content for all the aerated treatments was consistently slightly less than the soil moisture in the corresponding control. Moreover, the average soil water content between 20-40 cm below the soil surface

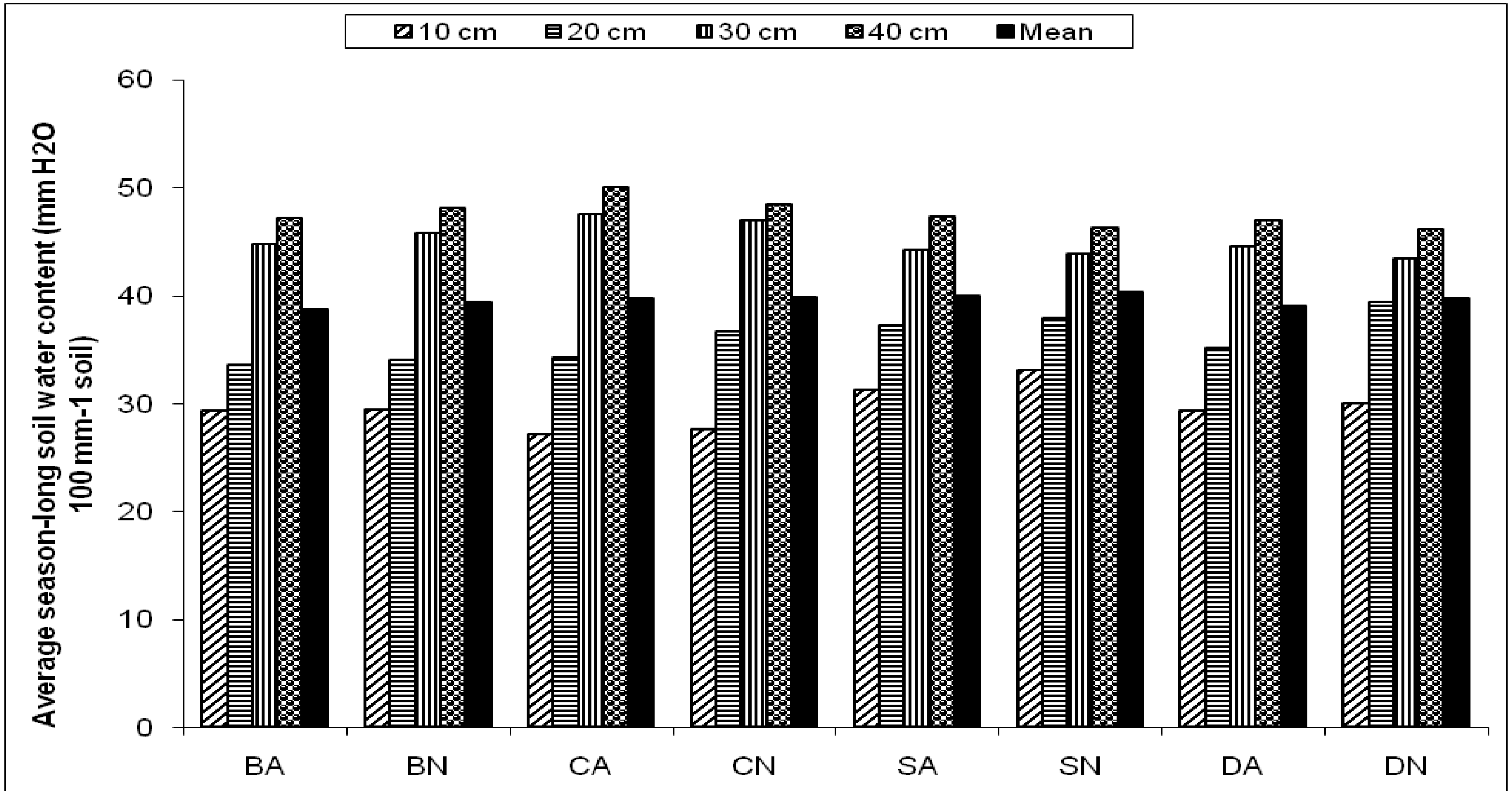

Figure 6. 2 Average season-long soil moisture with standard error bars for the vegetables in Chapter 6. BA, CA, SA, and DA denote aerated beetroot, pak choi, spring onion, and bean, respectively. BN, CN, SN, and DN denote control beetroot, pak choi, spring onion, and bean, respectively.

for all the treatments was above field capacity, indicating excess soil moisture within the lower half of the root zone depth.

The average measured air flow rates from the emitters for each block in the aerated treatments are presented in Table 6.1. Generally, for all the aerated treatments the average emitter air flow rate in the first (the closest to the venturi), second, third, and fourth block was 8, 5, 4, and 3 L h^{-1}, respectively. The average air flow rate over the entire blocks in each treatment was 5 L h^{-1}. The measured efficiency of air bubble delivery (i.e. the ratio of total air supplied by the venturi to the total air delivered by the emitters) for all aerated treatments was 93%. The average dissolved oxygen measured in the irrigation water tank was 7 mg L^{-1}.

The non-uniformity in the distribution of air flow rates along the irrigation pipe impacted on the water delivery of emitters (e.g. for the aerated spring onions, Table 6.2). In the first block, where the highest air flow rate was measured from the emitters (Table 6.1), the average water flow rate when air and water were flowing through the pipe was 42% less than the case when water alone was in the pipe. For the second, third, and fourth block, the relative difference of the average water flow rate between the foregoing cases dropped to 17%, 17%, and 8%, respectively.

Table 6. 1 Average emitter air flow rates (in L h^{-1}) across the aerated blocks for the vegetable species.

Vegetable species	Block 1	Block 2	Block 3	Block 4	Mean air flow rate for the entire treatment
Pak choi	8	5	4	3	5
Bean	8	5	4	3	5
Spring onion	8	5	4	3	5
Beetroot	8	4	4	3	5

Table 6. 2 Emitter water flow rates in the aerated blocks of spring onion (in L h^{-1} $emitter^{-1}$) for two cases.

	Block 1	**Block 2**	**Block 3**	**Block 4**
Case a*	1.2	1.2	1.2	1.2
Case b§	0.7	1.0	1.0	1.1
Relative difference (%)	42	17	17	8

*: Water alone was discharged from the emitters. §: Air and water were discharged from the emitters.

The estimated total available oxygen per pot was calculated as the summation of the amount of oxygen supplied via oxygation (for the aerated treatments only), dissolved oxygen in the irrigation water, and the oxygen in the soil air-filled porosity remained at the end of the irrigation (for both control and aerated treatments) (Table 6.3). Evidently, as the soil water content decreases, the required volume of irrigation

Table 6. 3 Illustrative estimated total oxygen per pot at the end of an irrigation event.

Treatment	**Soil water content before irrigation (mm H_2O 100 mm^{-1} soil)**	**Irrigation time (min)**	**Volume of irrigation water per pot (L)**	**Total available oxygen per pot (mg)**
Control beetroot	39.3	52	1.03	562
Control bean	39.7	46	0.92	562
Control pak choi	39.9	44	0.88	562
Control spring onion	40.3	38	0.77	561
Aerated beetroot	38.7	61	1.21	1733
Aerated bean	39.0	56	1.13	1751
Aerated pak choi	39.7	46	0.92	1571
Aerated spring onion	40.0	43	0.86	1454

water increases. Therefore, for a given emitter flow rate, to deliver the increased volume of irrigation water, the irrigation time should increase, accordingly. The estimated total available oxygen per pot at the end of irrigation for the control treatments was the same; 562 mg. In contrast to the control treatments, the total calculated oxygen in the aerated treatments was over two to three times larger due to additional oxygen supply via oxygation.

6.3.2 Pak choi

Irrigation for both treatments commenced at 1020 h on June 19, 2008 (70 DAS) and continued for 52 minutes for the aerated treatment and 32 minutes for the control treatment. The difference in irrigation time for the treatments was due to the difference in their soil moisture deficit and aeration value. As irrigation commenced, soil oxygen concentration in both treatments declined (data for the first block shown, Figure 6.3). However, the level of soil oxygen in the aerated treatment was always higher than that in the control treatment.

Although the values of soil respiration rate and leaf photosynthetic rate for the aerated treatment were slightly greater than their corresponding values for the control, generally, the data for both treatments were so close to each other that the t-test indicated no significant difference at 10% level of confidence (Table 6.4). However, the average values of soil respiration rate and leaf photosynthesis rate for block 1 of the aerated treatment were significantly greater than the corresponding mean values for the entire aerated treatment as well as the control. Likewise, instantaneous water use efficiency (WUEi), the number of leaves and the weight of fresh leaves per unit area did not significantly differ between the aerated and control treatments. Figure 6.4 presents the relative difference between the measured

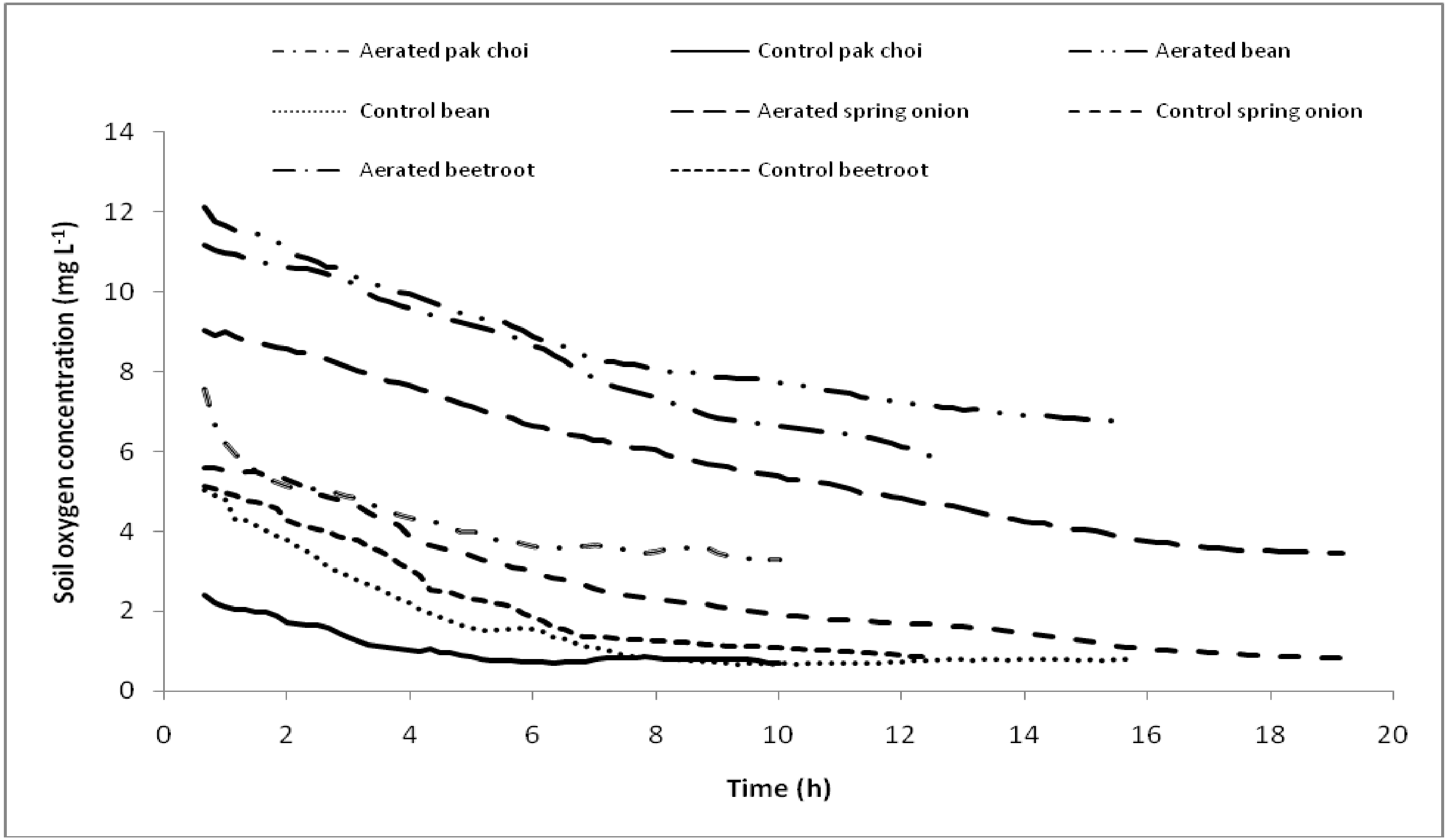

Figure 6. 3 Temporal variation in soil oxygen concentration of aerated vs. control vegetable species.

Table 6. 4 Soil respiration rate and growth characteristics for pak choi[1].

Treatment	Soil respiration rate (g CO_2 m^{-2} h^{-1})	Rate of leaf transpiration (mmol $m^{-2}s^{-1}$)	Stomatal conductance (mol $m^{-2}s^{-1}$)	Rate of leaf photosynthesis (μmol CO_2 $m^{-2}s^{-1}$)	WUEi[2]	Leaf count per m^{-2}	Weight of fresh leaves (g m^{-2})
Aerated	0.43	1.74	0.07	13.44	134	345	1930
Control	0.42	1.81	0.08	12.95	138	354	2417
t_{14df}	0.196	0.227	0.259	0.283	0.236	0.287	0.895
Block 1 (Aerated)	0.77 (t_{8df} = 8.359)[3]	2.03 (t_{8df} = 0.799)	0.10 (t_{8df} = 0.366)	17.24 (t_{8df} = 1.915)	170 (t_{8df} = 0.917)	375 (t_{8df} = 0.623)	2283 (t_{8df} = 0.122)

[1]: The critical t value for df = 14 and P<0.10 is 1.761, [2]: Instantaneous water use efficiency, μmol of CO_2 fixed per mmol of H_2O transpired, [3]: The calculated t value for block 1 and the control; the critical value for df = 8 and P<0.10 is 1.860.

parameters in Table 6.4 for the control and the corresponding parameters for the first block of the aerated one. Except for the leaf weight, all the other parameters showed positive response to root zone aeration. The highest enhancement was 83% - for soil respiration rate.

6.3.3 Dwarf bean

Soil oxygen concentrations for the aerated and control treatments are presented in Figure 6.3. Irrigation of the treatments started at 1235 h on July 30, 2008 (110 DAS) and continued for 83 minutes for the aerated treatment and 71 minutes for the control. Owing to the difference in soil moisture deficit and aeration value, the irrigation times for the treatments were proportionally different. The commencement of irrigation was followed by decrease in the soil oxygen in both treatments. But, the level of soil oxygen in the aerated treatment was always higher than that in the control.

Despite the slight enhancement in the leaf count, and leaf and stem weights for the aerated treatment, no significant difference was observed between the

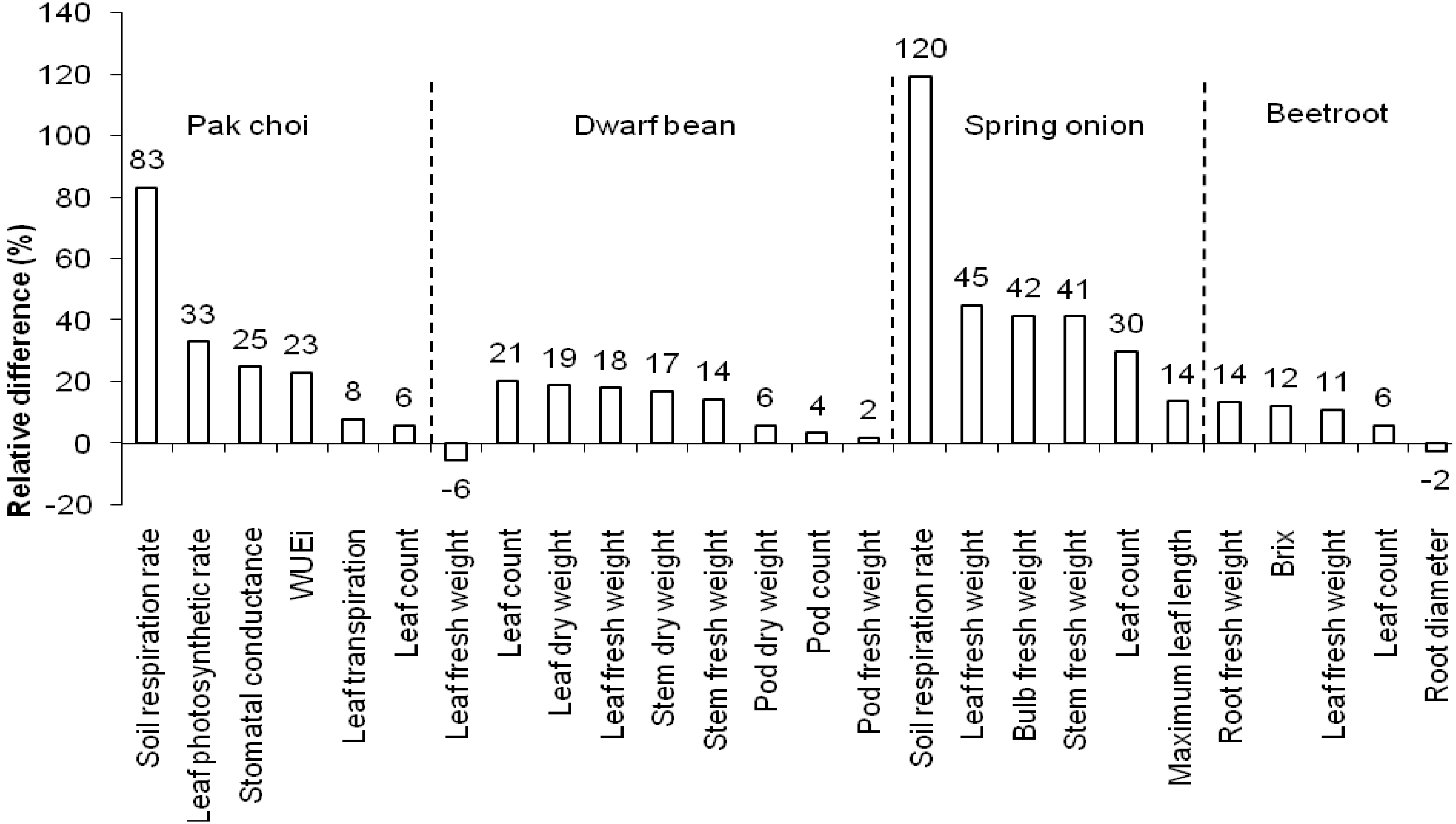

Figure 6. 4 Relative difference in performance between the aerated treatment in block 1 and the mean values for the entire blocks of the control treatment for four vegetable species.

treatments at a 10% level of confidence (Table 6.5). However, the average values of the vegetative growth parameters (such as leaf count, leaf and stem weight) for block 1 of the aerated treatment, where the plants received the highest average air flow rate, were significantly greater than the corresponding mean values for the entire control treatment. Figure 6.4 presents the relative difference between the measured parameters in Table 6.5 for the control and block 1 of the aerated treatment. The vegetative components such as leaf count, and the weight of leaf or stem showed the highest response to aeration, ranging from 21 to 14%, whereas the productive component (pod count and pod weight) were improved by only 2 to 6%.

Table 6. 5 Harvest data for dwarf bean[1].

Treatment	Pod count per m^{-2}	Pod fresh weight (g m^{-2})	Pod dry weight (g m^{-2})	Leaf count per m^{-2}	Leaf fresh weight (g m^{-2})	Leaf dry weight (g m^{-2})	Stem fresh weight (g m^{-2})	Stem dry weight (g m^{-2})
Aerated	346	2533	283	964	671	153	752	223
Control	362	2747	317	901	668	159	714	198
t_{14df}	0.617	1.253	1.399	0.648	0.039	0.395	0.506	0.732
Block 1 (Aerated)	375 (t_{8df} = 0.480)[2]	2803 (t_{8df} = 0.376)	335 (t_{8df} = 0.854)	1086 (t_{8df} = 1.946)	789 (t_{8df} = 2.633)	190 (t_{8df} = 1.960)	817 (t_{8df} = 1.912)	231 (t_{8df} = 2.248)

[1]: The critical t value for df = 14 and P<0.10 is 1.761, [2]: The calculated t value for block 1 and the control; the critical value for df = 8 and P<0.10 is 1.860.

6.3.4 Spring onion

Soil oxygen concentrations for the aerated and non-aerated treatments are presented in Figure 6.3. Irrigation of the treatments started at 0937 h on August 8, 2008 (119 DAS) and continued for 95 minutes for the aerated treatment and 89 minutes for the control. Due to the difference in soil moisture deficit and aeration value, the irrigation times for the treatments were proportionally different. As irrigation began, soil air was replaced by water and consequently the soil oxygen level in both treatments started to decrease. The soil oxygen concentration in the aerated treatment was always higher than that in the control.

Consistently, all the growth parameters (soil respiration rate and growth characteristics including the maximum leaf length, leaf count and fresh weights of leaves, stems, and bulbs per unit square metre) responded positively to oxygation (Table 6.6). However, the magnitude of response to root zone aeration was not the same for all the parameters. Despite the 11% relative difference in leaf count per unit area between the aerated and control treatments, the treatments did not show

Table 6. 6 Soil respiration rate and harvest data for spring onion[1].

Treatment	Soil respiration rate ($g\ CO_2\ m^{-2}\ h^{-1}$)	Leaf count (per m^2)	Maximum leaf length (mm)	Fresh leaf weight ($g\ m^{-2}$)	Fresh stem weight ($g\ m^{-2}$)	Fresh bulb weight ($g\ m^{-2}$)
Aerated	0.76	488	630	2024	827	354
Control	0.41	440	580	1667	697	277
t_{14df}	4.373	1.604	3.495	2.262	1.787	3.274
Block 1 (Aerated)	0.90 (t_{8df} = 8.467)[2]	572 (t_{8df} = 3.864)	660 (t_{8df} = 5.302)	2419 (t_{8df} = 4.558)	985 (t_{8df} = 2.900)	392 (t_{8df} = 3.550)

[1]: The critical t value for df = 14 and $P<0.10$ is 1.761, [2]: The calculated t value for block 1 and the control; the critical value for df = 8 and $P<0.10$ is 1.860.

significant difference at $P<0.10$ for this parameter. All the other parameters for the aerated treatment were significantly different from the control at $P<0.10$. Furthermore, corresponding data in the first block for the aerated treatment were significantly larger than the average values of the control treatment. The relative difference between the measured parameters in Table 6.6 for the control and block 1 of the aerated one is presented in Figure 6.4. Similar to pak choi, soil respiration rate in the first block of the aerated spring onions showed the highest enhancement (120%) as a result of root zone aeration.

6.3.5 Beetroot

Figure 6.3 presents the soil oxygen concentration for the aerated and control treatments. Irrigation started at 1220 h on July 19, 2008 (100 DAS) for both treatments and continued for 127 minutes for the aerated treatment and 96 minutes for the control. Because of the difference in soil moisture deficit and aeration value, the irrigation times for the treatments were proportionally different. During irrigation, soil air in both treatments was replaced by irrigation water. Expulsion of air from the soil pores led to a reduction in the soil oxygen level in the control treatment as well as the aerated one. However, due to the supply of air to the root zone during the irrigation event in the aerated treatment, the soil oxygen concentration in the aerated treatment was higher than that in the control. Plant response was assessed in terms of the leaf count, weight of fresh leaves, fresh root and root diameter (for the storage part only) and Brix for the aerated and control treatments (Table 6.7). Although the values for leaf count per unit area, and Brix for the aerated treatment were slightly larger than the corresponding values for the control, generally the aerated treatment did not differ significantly from the control. Moreover, the corresponding data in the first block for the aerated treatment were significantly bigger than the average values of the control except for the root diameter. Root diameter in block 1 for the aerated treatment was 2% smaller than the corresponding value for the control (Figure 6.4).

Table 6. 7 Harvest data for beetroot[1].

Treatment	Leaf count (per m^2)	Leaf fresh Weight (g m^{-2})	Root fresh weight (g m^{-2})	Brix (%)	Root diameter (mm)
Aerated	367	1677	1917	12.1	49
Control	365	1764	1993	11.9	51
t_{14df}	0.318	0.812	0.672	0.266	0.460
Block 1 (Aerated)	386 (t_{8df} = 2.116)[2]	1958 (t_{8df} = 2.247)	2194 (t_{8df} = 2.175)	13.3 (t_{8df} = 1.997)	50 (t_{8df} = 0.052)

[1]: The critical t value for df = 14 and P<0.10 is 1.761, [2]: The calculated t value for block 1 and the control; the critical value for df = 8 and P<0.10 is 1.860.

6.3.6 SPAD results across species

There was significant interaction between aeration and species. General analysis of variance on SPAD readings of all the species indicated significant difference between aerated and non-aerated treatments for spring onion at P<0.10, whereas no significant interaction was found between aeration and block effect (Table 6.8). SPAD readings in the aerated spring onion were remarkably greater than the readings for the non-aerated one. For pak choi the reverse trend was evident, and

Table 6. 8 Analysis of variance for SPAD readings.

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	F Probability
Block stratum	3	73.946	24.649	4.36	
Aeration	1	40.641	40.641	7.19	0.010
Species	3	4075.412	1358.471	240.37	<0.001
Block*Aeration	3	14.27	4.76	0.05	0.984
Species*Aeration	3	125.022	41.674	7.37	<0.001
Residual	53	285.267	5.562		
Total	66	4614.558			

barely significant. No significant difference in SPAD readings was observed between the aerated and non-aerated treatments of beetroot or bean (Figure 6.5).

6.4 Discussion

In contrast to the extremely low efficiency of air bubble delivery (3%) from the branching pipe system and symmetric connectors in the oxygation of sorghum in Chapter 4, utilization of a single lateral pipe and asymmetric connectors for oxygation of the vegetable species resulted in delivery of almost the entire volume of air bubbles (93% efficiency of air bubble delivery) supplied by the venturi to all the oxygated pots. However, the data in Table 6.1 clearly indicate a decreasing trend of the air flow rates along the lateral pipes. The asymmetric connectors created local turbulence around the entrance of the connectors which led to elevated availability of air bubbles for the proximal emitters and thereby a greater mean air flow rate. A more detailed discussion on how asymmetric connectors aggravate the non-uniformity of air flow rate along a lateral line is provided in section 3.4.1.3 of Chapter 3.

The remarkably high air flow rates from the emitters which were closer to the air injector venturi resulted in decreased water flow rates in those emitters. This is further supported by similar results from asymmetric connectors, presented in sub-sections 3.3.4.1 and 3.3.4.2 in Chapter 3. Possibly, the relative reduction in water flow rate of the emitters which were closer to the venturi could be responsible for the longer irrigation time in the aerated treatments compared to the control (Table 6.3).

Total available oxygen in the oxygated pots was over two to three times by weight greater than total oxygen in the control pots (Table 6.3). Indeed, the source of oxygen in the control treatments was restricted to the dissolved oxygen in the

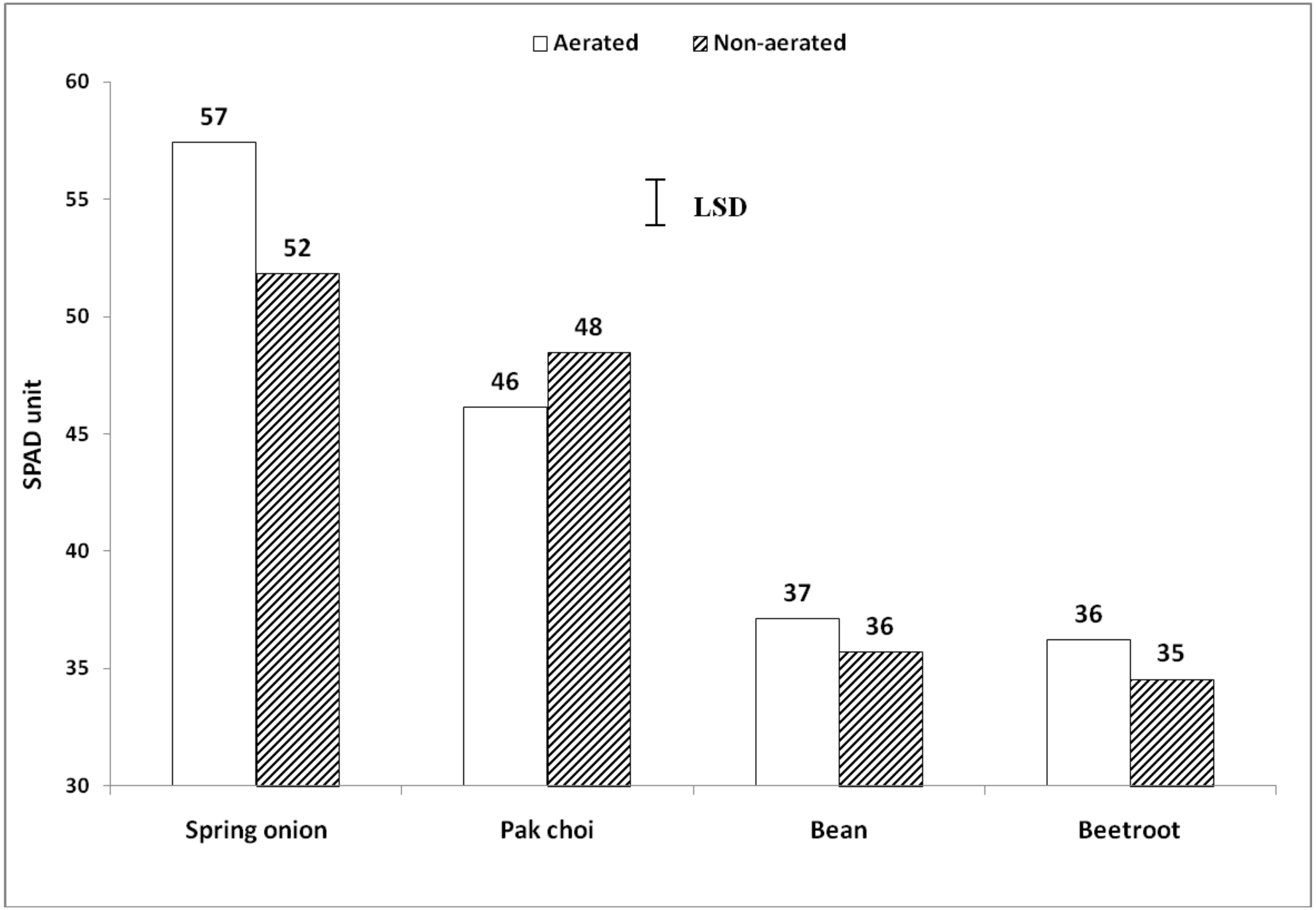

Figure 6. 5 The influence of root zone aeration on leaf chlorophyll content (15 df, LSD = 2, P<0.10) in four vegetable species.

irrigation water (7 mg L^{-1}) and the soil air-filled porosity at the end of irrigation. The solubility of oxygen in water at a given pressure is very small, relative to the O_2 content of air, and decreases rapidly as the temperature and/or electrical conductivity of water increases. Further, the rate of O_2 diffusion through a gas is 10,000 times faster than that through water. Also, the amount of oxygen supplied from the soil air-filled porosity is not notable because usually irrigation is done to bring the soil water content up to the field capacity where most of the soil pores are filled with water and only a few (~ 8% by volume for the soil type in this experiment) remain air-filled. For estimation of oxygen volume in the soil air-filled porosity, it was assumed that oxygen constitutes about 21% of the air volume whereas the air constitution in the soil is different from that in the ambient air such that O_2 volume is usually less than 21% of the soil air (Brady & Weil 1999). Oxygen concentration at 20 cm in a daily drip irrigated tomato crop at 100-120% ETc in a clay soil reportedly varies between 30-60 mL L^{-1} (Meek et al. 1983).

In addition to dissolved oxygen in the irrigation water and the amount of oxygen from the air-filled pores of the soil, the main source of oxygen supply to the aerated treatments was the flow of air bubbles supplied by the air injector venturi. The markedly higher amount of oxygen content in the aerated treatments compared to the controls is further supported by the measured soil oxygen concentration during and post-irrigation as presented in Figure 6.3. It should be mentioned that soil oxygen concentration for control pak choi (Figure 6.3) in contrast to the measured soil oxygen concentration for the control bean, spring onion, and beetroot was very low. The reason was that the water tank of that treatment was covered for two days before commencement of that particular irrigation event, which caused impediment to diffusion of ambient air into the irrigation water.

Although all the aerated treatments received the same rate of air flow (5 L h^{-1} on average) within their root zone (Table 6.1), oxygation did not cause significant enhancement in the performance of the experimental species other than for spring onion. Nonetheless, this does not indicate that oxygation did not absolutely have any positive effect on the performance of pak choi, bean, and beetroot. First, a relatively high sensitivity of spring onion to waterlogging (Nicholson & Shaw 2003) might be responsible for the significant performance of the aerated treatment of this species. Huang and Johnson (1995) studied the response of two wheat genotypes differing in waterlogging tolerance to hypoxia and subsequent resumption of full aeration grown in nutrient solution culture. The genotypes were C9835 (waterlogging-sensitive) and Jackson (waterlogging-tolerant). The aeration treatments were hypoxia or aerated (control) continuously for twenty one days, and a seven day recovery (i.e. hypoxia for fourteen days followed by seven days aeration). The hypoxia treatments received 5% O_2 by volume at 500 mL min^{-1}. For the aerated controls, ambient air was introduced into the nutrient solution at 1500 mL min^{-1}. Table 6.9 presents the responses of root and shoot growth of the two genotypes to hypoxia and subsequent resumption of full aeration. Clearly, the waterlogging-sensitive genotype (C9838) showed more improvement in both root and shoot growth than did the waterlogging-tolerant genotype (Jackson) after seven days of recovery from hypoxia. A similar sensitivity might explain why spring onion as a species which is very sensitive to excess soil moisture (Nicholson & Shaw 2003), responded significantly to oxygation in contrast to other vegetable species. Second, it is evident from Figure 6.4 that the plants in the first block of the aerated treatments generally performed better than the plants in the corresponding control treatments. Third, from Tables 6.4-6.7, it can be seen that most of the measured parameters in first block of the aerated treatments are significantly larger than the corresponding parameters for the entire control treatment; implying that oxygation has the potential to improve crop growth and increase the yield. This is attributed to the higher average air flow rate in block 1 of the aerated treatments (Table 6.1). Similar results have been observed in the first block of the aerated wheat (Chapter 7) and soybean (Chapter 8).

Table 6. 9 Response of two different wheat genotypes to hypoxia (adapted from Huang & Johnson 1995).

	Genotype	LCRL* (cm)	Dry root weight (g)	Dry shoot weight (g)
Response to 21 d of hypoxia	C9838	13.88	0.53	2.53
	Jackson	26.75	1.04	3.65
Root and shoot growth after 7 d of recovery from hypoxia	C9838	32.33	1.72	6.57
	Jackson	43.67	1.89	8.53
Relative difference (%)	C9838	133	224	160
	Jackson	63	82	134

*LCRL, length of the longest crown root.

The remarkably enhanced performance of the plants in the first block of the aerated treatments suggests that if at least the same air flow rates as those in the first block of the aerated treatments were supplied to the other aerated blocks, they would be able to perform significantly better than their corresponding control treatment. It seems that the declining air flow rate along the irrigation pipe in the aerated treatments led to delivery of insufficient air to make a positive difference to the root zone of the second, third and fourth blocks. It should be noted that the decreasing trend in the air flow rate distribution of the aerated treatments is in agreement with the results mentioned in section 3.3.1 of Chapter 3. There are articles presenting significant response of vegetable soybean (Bhattarai, Huber & Midmore 2004), tomato (Bhattarai, Pendergast & Midmore 2006), and chickpea (Bhattarai, Midmore & Pendergast 2008) to oxygation. However, since no information about factors influencing the efficacy of oxygation including piping layout (branching or single pipe), connector type (symmetric or asymmetric), and lateral pipe diameter is mentioned in the articles, it is not possible to compare them with the results obtained in this experiment.

Plants employ a variety of mechanisms to cope with anaerobic conditions such as formation of aerenchyma, adventitious roots, and shallow rooting (Laan et al. 1989). Some species such as pak choi develop shallow roots close to the soil surface where they gain access to more air. Figure 6.6 shows a pot containing pak choi in the control treatment. The tiny white tips of the pak choi roots were visible on the soil surface. It is possible that such shallow roots were developed in the aerated pots as well. However, owing to the smaller amount of available oxygen in the control

Figure 6. 6 Shallow roots of pak choi on the soil surface.

treatment compared to the aerated one (Table 6.3), the density of the shallow roots in the control was possibly greater than in the aerated treatment. In contrast to the non-significant response of pak choi to oxygation in this experiment, Bhattarai, Salvadon and Midmore (2008) reported a marked effect of oxygation on Chinese cabbage in a hydroponic system. In their experiment, irrigation was imposed two-three times a day for four-six hours using 1.0 L h^{-1} emitters. The aerated treatment received 12% air by volume of water via a Mazzei air injector venturi. The aerated water contained 5-15 ppm dissolved oxygen whereas the non-aerated water contained 0-5 ppm when measured in the holding tank. Dry matter yield, leaf photosynthesis, and water use efficiency (calculated as total dry weight per unit of accumulated water use by transpiration) for the aerated treatment increased by 12%, 11%, and 39% compared to the control, respectively. It is likely that the positive response of Chinese cabbage to oxygation was due to the frequent aeration (two-three times a day) of the plants and the relatively long oxygation time (four-six hours) compared to about one hour (on average) every other day oxygation for pak choi in the present experiment.

The positive response of Chinese cabbage to oxygation recorded by Bhattarai, Salvadon and Midmore (2008) suggests that using very low flow rate emitters (e.g. <0.5 L h^{-1}), also known as microdrip emitters (Assouline 2002), instead of conventional ones ($\geq$ 2.0 L h^{-1}) evidently increases the oxygation time for delivery of a given volume of water to the root zone. In Chapter 3, it was shown that a 242% relative reduction in emitter water flow rate (i.e. from 4.1 L h^{-1} to 1.2 L h^{-1}) caused a remarkably small relative reduction in the average emitter air flow rate of 59%. Hence, using microdrip emitters instead of conventional ones ($\geq$ 2.0 L h^{-1}) will increase the irrigation time without possibly significant reduction in the delivery of air flow rates from the emitters. A further improvement in crop yield would be likely if provisions are made to attain a uniform air flow rate distribution along the lateral line so that every oxygated plant would receive a sufficient amount of oxygen. Application of surfactants could be a solution to enhance the uniformity of air flow rate distribution along a pipe via reduction of water surface tension as well as air bubble diameter, and consequently increase in the number of air bubbles which leads to improved availability of air bubbles to the remote emitters. Utilization of a non-ionic and biodegradable type surfactant will minimize the risk of interference and/or interaction with the soil nutrients and environmental hazards. In Chapter 3, the effect of surfactant on the uniformity of air flow rate is discussed in detail. In addition to the Mazzei air injector, utilization of oxyfertigation or Seair™ might be options for root zone aeration. In the oxyfertigation technique, a sealed air injector chamber is connected to a small-pore diffuser near the outlet assembly of the drip irrigation system where dissolved oxygen concentration as high as 25.6 mg L^{-1} is deliverable (Marfa, Caceres & Guri 2005).

In the Seair aeration technique, air bubbles supplied by an air injector venturi are directed into a diffusion chamber where gas bubbles at 5μm (Scott et al. 2008) allow for super aeration of the irrigation water.

Some crop species such as bean, sunflower, tomato (Kawase 1981), barley (Arikado & Adichi 1955), rice (Justin & Armstrong 1991), maize (Gunawardena et al. 2001), soybean (Bacanamwo & Purcell 1999), and wheat (Wiengweera, Greenway & Thomson 1997; Watkin, Campbell & Greenway 1998) form aerenchyma under low soil oxygen concentration conditions and improve root aeration via delivery of air and oxygen from the shoot. Aerenchyma is a soft tissue containing large intercellular spaces capable of providing internal pathways of low resistance for circulation of gases between shoot and root (Jackson & Armstrong

1999). Formation of aerenchyma in the control beans might have been responsible for the lack of significant difference between the aerated and control treatments.

Zhang and Greenway (1994) have shown that aged storage tissues of beetroot survived anoxia for 150 hours at 20 ºC. This ability of beetroot in withstanding anaerobic conditions may explain the non-significant difference between aerated and non-aerated treatments of this species. In addition, Vyrlas and Sakellariou-Makrantonaki (2005) reported non-significant enhancement in yield and yield components of sugar beet (a close relative to beetroot) from root zone aeration in a clay loam soil. The treatments consisted of aerated (continuously via the Mazzei air injector venturi, intermittently, and after irrigation delivering by means of an air compressor) and non-aerated (control) plots. In the continuously aerated plots, the Mazzei supplied 12% air by volume of water. Unfortunately, no details were provided about aeration in the intermittent or post-irrigation aerated treatments. Root yield, sugar yield, polarization, potassium, sodium and amino nitrogen values measured in the harvested samples indicated a relatively higher but not statistically significant difference between the aerated treatments and the control. The non-significant response of beetroot in my experiment and the long duration tolerance of beetroot tissues to hypoxia as well as the non-significant response of sugar beet to root zone aeration suggests that beetroot intrinsically has a relatively higher tolerance to excess soil water content in comparison with spring onion. Furthermore, during the growing season, part of the beet root was above the soil surface (up to about 10 mm) and some feeder roots anchored to the surface. It is likely that similar to the pak choi plants, the beetroot plants gained access to air via the shallow roots.

Analysis of variance on the SPAD readings of the aerated vs. control treatments for the vegetable species revealed that aeration of the root zone significantly influenced the SPAD readings for spring onion and pak choi only. The significantly higher leaf chlorophyll content in the aerated treatment of spring onion (Figure 6.5) in contrast to the control is attributed to the significantly improved soil environment - reflected by the higher respiration rate in the aerated treatment (Table 6.6). It is expected that enhanced root respiration as a result of improved root zone aeration would further promote water and nutrient uptake (Bhattarai, Su & Midmore 2005) and thereby likely increase leaf chlorophyll content. For pak choi, despite the non-significant difference between the soil respiration rates of the treatments (Table 6.4), the leaf chlorophyll content in the control was apparently higher than the aerated treatment. However, the absolute difference between the values (46 vs. 48, LSD (53 df) = 2; Figure 6.5) was equal to the precision of the apparatus (±2 SPAD units) (Bhattarai, Huber & Midmore 2004), indicating a marginal significance only.

6.5 Conclusion

Utilisation of a recirculating drip irrigation system with a single pipe and asymmetric connectors for simultaneous delivery of air and water to the root zone of the experimental treatments led to non-uniform declining air flow rates across the aerated blocks. The very high air flow rates particularly from the emitters in the first block, resulted in decreased emitter water flow rate.

In all the aerated treatments, for the maintained pressure differential across the venturi, the pots in the first block received the highest rate of air flow (8 L h^{-1}). It seems that this level of air flow rate during irrigation events was sufficient to markedly enhance the performance of all the experimental species in the first block, in contrast to the other aerated or non-aerated blocks. However, the non-uniform distribution and decreasing rate of emitter air flow along the lateral pipes of the aerated treatments led to insufficient supply of oxygen to cause a difference in the distal blocks which in turn caused non-significant differences in plant performance for the majority of the experimental species.

The estimated total oxygen available to the plants in the aerated pots was about 3 times larger than that in the non-aerated pots; however, except for spring onion, the other species did not show significant response to the level of root zone aeration supplied in this experiment. It is likely that the relatively high sensitivity of spring onion to water logging was responsible for the significant enhancement of that species' performance.

Crop species employ a variety of mechanisms to cope with the adverse effects of hypoxia. Possibly, the intrinsically high tolerance to hypoxia (in beetroot), or shallow rooting (in pak choi), or aerenchyma formation (in bean) was responsible for the non-significant difference of the plant performance between the aerated and non-aerated treatments.

Based on the irrigation settings used in this experiment, the primary constraints to efficacy of oxygation for crop species are insufficient supply of oxygen to plant root zone and non-uniform distribution of air bubble delivery along a lateral line. One approach could be to redesign the irrigation system by using microdrip emitters instead of the conventional ones (particularly for fine textured soils), for delivery of more oxygen to the root zone via increasing the oxygation time for a given volume of water, without considerable reduction of the emitter air flow rates.

To improve the uniformity of air bubble distribution along a lateral line, one possible solution is to reduce the surface tension of the aerated water and thereby increase the number of air bubbles due to reduction in the diameter of the air bubbles. The resulting increase in the number of air bubbles leads to availability of more air bubbles to the remote emitters. Using appropriate concentration of a non-ionic biodegradable surfactant in the irrigation water will not only help to enhance the uniformity of air bubble distribution, but also minimizes the risk of interference with the soil nutrients (as non-ionic surfactants lack electric charges) and environmental hazards due to degradation by soil microorganisms. Another approach might be utilization of alternative oxygation methods such as oxyfertigation or the Seair aeration technique to enhance root zone aeration.

Chapter 7: Effect of soil type and techniques of aerating irrigation water on wheat

ABSTRACT

This study was initiated to explore the effect of aerating irrigation water through either a venturi based air-water mixing system (using a Mazzei air injector venturi) or a diffusion-based super aerated water (using a Seair Diffusion Chamber) on the performance of a wheat crop on two soil types: black Vertisol and red Ferrosol.

The season-long average degree of saturation over the soil profile for the Vertisol and Ferrosol was 0.68 and 0.45, respectively, indicating higher soil water content as well as poorer internal drainage for the Vertisol compared to the Ferrosol. This was attributed to the lower permeability of the Vertisols.

The average air flow rate and the associated Christiansen's uniformity coefficient (CUC) for the Mazzei air injector were ~ 0.90 L h^{-1} and 21%, respectively, whereas those measured for the Seair were ~ 0.81 L h^{-1} and 33%, respectively. Both aeration treatments showed non-uniform emitter air flow rate distribution along the lateral pipes with the highest average air flow rates delivered by the emitters proximal to the venturi.

Generally, the aerated treatments showed enhanced performance in comparison with the control, with the Mazzei treatment delivering consistently higher outcomes than the Seair. However, these differences were not significantly different at P <0.10, with the exception of the leaf chlorophyll concentration. The non-significant differences between the aerated treatments and the control were attributed to the insufficient emitter air flow rates and to air bubbling at the soil

surface. The significantly higher leaf chlorophyll concentration of the plants grown on the Ferrosol in contrast to that on the Vertisol was possibly due to higher iron content in the Ferrosols.

7.1 Introduction

Transitory flooding or prolonged irrigation accompanied by poor drainage may impede root respiration through restriction on the availability of soil oxygen. Waterlogging and insufficient soil aeration results in anaerobic conditions. In flooded or waterlogged soils, oxygen shortage is considered as one of the main root stresses (Kozlowski 1984). Waterlogging can adversely affect some physiological processes such as shoot and root hormone relations (Huang et al. 1994), uptake and transport of ions through roots leading to nutrient deficiencies (Trought & Drew 1980; Hodgson, Whitely & Bradnam 1989; Huang et al. 1995), and water absorption (Drew 1991). Adverse effects related to waterlogging include build-up of poisonous substances such as Mn^{2+}, Fe^{2+},H_2S, CO_2, ethylene, acetic acid, butyric acid, lactic acid, and abscisic acid (Ponnamperuma 1984; Huang et al. 1994), and nitrogen deficiency through the stimulation of leaching and denitrification (Hodgson, Whitely & Bradnam 1989; Huang et al. 1994). Waterlogging leads to reduction in kernel number, grain yield, and leaf elongation in cereals (Luxomore, Fisher & Stolzy 1973; Gardner & Flood 1993; Musgrave & Ding 1998). Waterlogging also enhances formation of aerenchyma and increases porosity of wheat roots (Huang et al. 1994), improves partition of carbohydrate to roots and decreases leaf carbohydrate content (Huang & Johnson 1995).

Collaku and Harrison (2002) studied the losses in yield and yield components and the trend response of wheat to 0, 10, 20, and 30 days of waterlogging. The results indicated significant linear and quadratic responses for chlorophyll content and yield, significant linear and cubic responses for plant height, and significant linear responses to increasing degrees of waterlogging for tillers per plant and kernels per head. Reduction in kernels per head and tiller number led to average yield losses of 44%. The reduction in kernels per head and tiller number were 20 and 41%, respectively. The linear response of a growth parameter to a given factor (e.g. waterlogging) indicates a simple relationship between them; an increase in the magnitude of the factor leads to a uniform increase/decrease in the magnitude of the growth parameter. In contrast to a linear response, a quadratic model presents a more complex behaviour of the growth parameter to the factor. There exists a critical value (i.e. *turning point*) for the factor, where the trend in the response of the growth parameter to the factor is reversed. Likewise, a cubic response is even more complicated than a quadratic one because there exist two critical values (i.e. *turning points*) where the trend in the response of the growth parameter to the factor is reversed twice.

Recent studies (Goorahoo et al. 2002; Bhattarai, Huber & Midmore 2004; Bhattarai, Pendergast & Midmore 2006) indicate the potential of using subsurface drip irrigation to provide aerated water to enhance crop performance under transient anaerobic conditions in the soil. Given the propensity of wheat to respond negatively to waterlogging, there is a strong likelihood that wheat will benefit from aeration of irrigation water, offsetting temporal anaerobiosis. In this experiment, wheat was grown on two soil types (Vertisol and Ferrosol) and supplied with aerated water by two techniques of water aeration (Mazzei air injector venturi and Seair diffusion system). The objectives of this study were to explore the effect of root zone aeration, and compare techniques of aeration, studying the responses of yield and growth parameters of wheat on two soil types.

7.2 Materials and Methods

The experiment was conducted in 16 concrete containers (referred to as tubs) at Central Queensland University, Rockhampton, Australia. The dimensions of each tub were 3.1 m × 0.85 m × 0.58 m (Figure 7.1). Eight tubs were filled with a black cracking clay soil (black Vertisol) and eight tubs were filled with a red clay soil (red Ferrosol). For the Ferrosol and Vertisol, the bulk density was maintained at 1.4 and 1.3 g cm^{-3}, the field capacity was 29 and 43 mm H_2O per 100 mm soil profile, total nitrogen was 22% and 15%, total phosphorous was 29 and 138 mg kg^{-1}, total potassium was 262 and 506 mg kg^{-1}, and pH was 6.4 and 7.4, respectively.

Figure 7. 1 The concrete containers (tubs) in the wheat experiment.

Wheat (*Triticum aestivum*) variety Kennedy was sowed at 5 cm depth in four rows parallel to the longitudinal axis of each tub on August 3 and harvested on October 10, 2008. The distance from the side wall of the tub to the first row was 12.5 cm, and the rows were 20 cm apart.

The experimental design was an unbalanced factorial completely randomized design (CRD) with two factors: soil type and oxygation method. The oxygation methods consisted of oxygation by means of Mazzei™ air injector venturi model 384, oxygation via Seair Diffusion System™ model SA75, and control (i.e. no aeration)[1]. The treatments involving Mazzei™ or Seair™ aerators were replicated three times and the control only twice for each soil type (Figure 7.2). The treatments are denoted as BS (Vertisol, Seair), BM (Vertisol, Mazzei), BC (Vertisol, Control), RS (Ferrosol, Seair), RM (Ferrosol, Mazzei), and RC (Ferrosol, Control).

RC2	BC1
BM3	RM1
RS3	RC1
BC2	BM1
BS3	BS1
RS2	RM2
BM2	RS1
RM3	BS2

Figure 7. 2 The layout of the experiment. The letters ‘B’, ‘R’, ‘M’, ‘S’, and ‘C’ stand for ‘black Vertisol’, ‘red Ferrosol’, ‘Mazzei’, ‘Seair’, and ‘Control’, respectively.

Within the Seair™ aerator, water was pumped from a water tank and flowed through a by-pass venturi system (Figure 7.3). The venturi was a Mazzei model 1584 and the pressure at the inlet and outlet of the mazzei was maintained at 165 and 124 kPa (24 and 18 psi), respectively. At this pressure differential, according to the Mazzei Injector Corporation Performance Table (n.d.), air will be introduced into the water at a rate of 580 L h^{-1}. The aerated water was then diffused into the patented

[1] The use of product names in this research is not an endorsement of the company’s product. These names are mentioned here primarily for the purpose of letting readers know where the relevant materials can be obtained.

Seair Diffusion Chamber™, where the pressure inside the chamber was maintained within 82.7-103.4 kPa (12-15 psi) in order to allow for super aeration of the water. The super aerated water was then returned into the water tank for oxygation use. This procedure (i.e. circulation of aerated water between the diffusion chamber and water tank) always continued for approximately two hours before commencement of oxygation of the treatments with Seair.

Oxygation by means of Mazzei was achieved using a model 384 air injector venturi. The pressure at the inlet and outlet of the venturi was maintained at 276 and 90 kPa (40 and 13 psi). According to the Mazzei Injector Corporation (n.d.), this pressure differential will introduce an air flow rate of approximately 48 L h^{-1} provided a motive water flow of at least 429 L h^{-1} is maintained. As pressurized water enters the inlet of venturi, its velocity increases in the throat of the injector. According to the Bernoulli principle, the increase the velocity of water at the throat of the venturi may lead to a decrease in pressure below atmospheric in that point. This drop in pressure causes air to be drawn into the suction port and be incorporated into the water flow.

Figure 7. 3 The Seair diffusion system used in the wheat experiment.

Each tub was irrigated by twenty Netafim™ pressure compensated 'PCJ' on-line drippers placed 10 cm below the soil surface. The water flow rate of the emitters was 2.0 L h^{-1} under an operating pressure range of 50-400 kPa (7.2-58 psi). The emitters were connected to asymmetric connectors spaced at 3 cm on the lateral pipe via 3.1 m long riser tubes of 4 mm diameter. Due to the relatively short distance between emitters, it was likely that each emitter might be influenced by the turbulence resulted from the preceding emitter. Hence, at each tub, an asymmetric goof plug (similar to the one shown in Figure 3.6, Chapter 3) was inserted in the lateral pipe 3 cm before the first emitter. For each treatment, a 19 mm ID lateral pipe was laid over eight tubs on one side of the experiment and eight on the other side in a U-turn shape (Figure 7.1) and the pressure at the return to the tank (the irrigation system was a recirculating one) was maintained in the range of 62-76 kPa (9-11 psi). The treatments were imposed 24 days after sowing.

Soil water content was measured every 1-3 days, just before the commencement of irrigation, in three access tubes per tub at 0-10, 10-20, 20-30, 30-40, and 40-50 cm from the soil surface. It was achieved by means of a calibrated Micro Gopher™ system (Soil Moisture Technology, Australia), the probe of which consists of a capacitance sensor. Based on the averaged soil moisture readings, irrigation was done every 1-3 days to refill the soil profile. All tubs were irrigated on the same day. The degree of soil saturation, defined as the ratio of soil moisture to total soil porosity (Delleur 2007), was calculated for both soil types at 10 cm depth intervals based on the season-long average soil water contents.

Soil temperature was recorded in every tub by a calibrated temperature sensor Tiny Tag Ultra™ Model TGU-1500 (Gemini Data Loggers, UK) placed 15 cm below the soil surface.

The soil oxygen concentration in RS1 and RC2 was recorded 59 DAS by an oxygen sensitive Fibox-3 oxygen meter (PreSens™ GmbH, Germany). The oxygen sensors were placed 15 cm below the soil surface and 10 cm from an emitter. Due to malfunction of the oxygen sensors, data on soil oxygen concentration were collected only for RS1 and RC2.

Performance of wheat in terms of plant phenology and growth parameters consisting of crop water stress index, leaf water potential, leaf chlorophyll concentration, and instantaneous water use efficiency was measured from four bordered plants in each tub. Crop water stress index was measured using a Model 210 Ag Multimeter (Everest Interscience™ Inc., Fullerton, CA) hand-held infrared thermometer. In each measurement, to avoid the influence of the soil background on the canopy temperature readings, the infrared thermometer was held above the plant canopy at an angle of 15 ºC below the horizontal so that only the plant parts were viewed by the infrared thermometer. In each determination, four canopy temperature measurements were taken from four sides and then averaged. These measurements were carried out between 1300-1500 h, 34 days after sowing. The CWSI was calibrated using internal software for wheat, and varies from 0 to 1 with 1 representing a plant having no transpiration and 0 representing a plant transpiring at the maximum rate (Irmak, Haman & Bastug 2000).

Midday leaf water potential of four fully-expanded leaves per tub was determined using the pressure bomb apparatus from Soil Moisture Equipment™ Corp., USA, following the procedure described by Scholander et al. (1965) 39 days after sowing.

Leaf chlorophyll concentration was measured on one fully expanded young leaf per plant using a Minolta SPAD-502™ chlorophyll meter (Konica Minolta Ltd, Japan). The wheat harvest data were obtained from 1 metre length samples taken from the middle two rows, 64 days after sowing. Harvest was before full maturity to allow for planting of genetically modified cotton within the stipulated ‘planting window’. Regulations imposed by Centre for Plant and Water Science for management of insect resistance in genetically modified cotton dictated the sowing window.

Instantaneous water use efficiency was calculated as the amount of CO_2 (μmol) fixed per unit of H_2O (mmol) lost by transpiration in photosynthesis. The inputs for this analysis were derived from the leaf IRGA data. The IRGA measurements were made on four fully expanded leaves per plot between 1000-1500 h, 64 days after sowing.

Number of tillers, number of ears, fresh weights and dry weights of the leaves, stems, and ears at harvest were recorded on the 0.2 m^2 plant sample removed for yield analysis.

Air flow rate from emitters were measured for the oxygated treatments with the same method as described in Chapter 3. From each tub, five emitters were selected for air flow measurements. The selected emitters in each tub were the first, the fifth, the tenth, the fifteenth, and the twentieth emitter on the lateral line.

The collected data were subject to the two-way analysis of variance at $P<0.10$ using GenStat version 10.1.

7.3 Results

The variation in soil water content at 10 cm depth intervals within the tubs for the two types of soils is presented in Table 7.1. The average soil moisture for the treatments with Vertisol and Ferrosol was approximately 20% and 30% below the corresponding field capacity, respectively. The degree of soil saturation for both soil types at 10 cm depth intervals is presented in Figure 7.4. From Figure 7.4, it is evident that soil water content for Vertisols over the entire soil profile was higher in comparison with Ferrosols.

Table 7. 1 Average of season-long soil water content (in mm H_2O 100 mm^{-1} soil) for the two soil types in the wheat experiment.

Soil depth (cm)	Soil type	
	Vertisol	Ferrosol
0-10	18.7	14.4
10-20	27.4	17.2
20-30	36.8	19.9
30-40	42.3	23.3
40-50	47.4	29.8
Mean	34.5	21.0

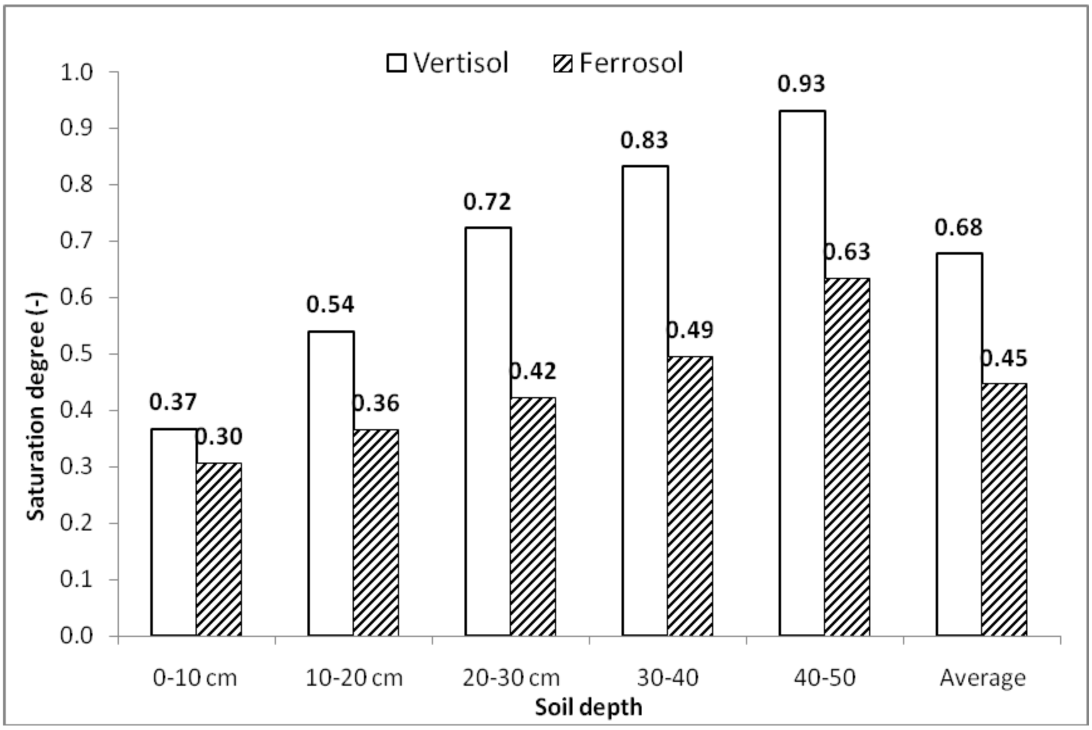

Figure 7. 4 The seasonal average soil degree of saturation for Vertisols Ferrosols over the soil profile.

The season-long mean soil temperature (at 15 cm depth) of the treatments is shown in Figure 7.5. In the treatments with Vertisol (BC, BM, and BS), the average soil temperatures were very close to each other and the same was true for the treatments with Ferrosol (RC, RM, and RS). Vertisol was on average 2 °C warmer than Ferrosol. There was a definite tendency for the control treatment in both soil types to have the lowest average soil temperature; the Mazzei treatment the highest and the Seair treatment intermediate between both (Figure 7.5).

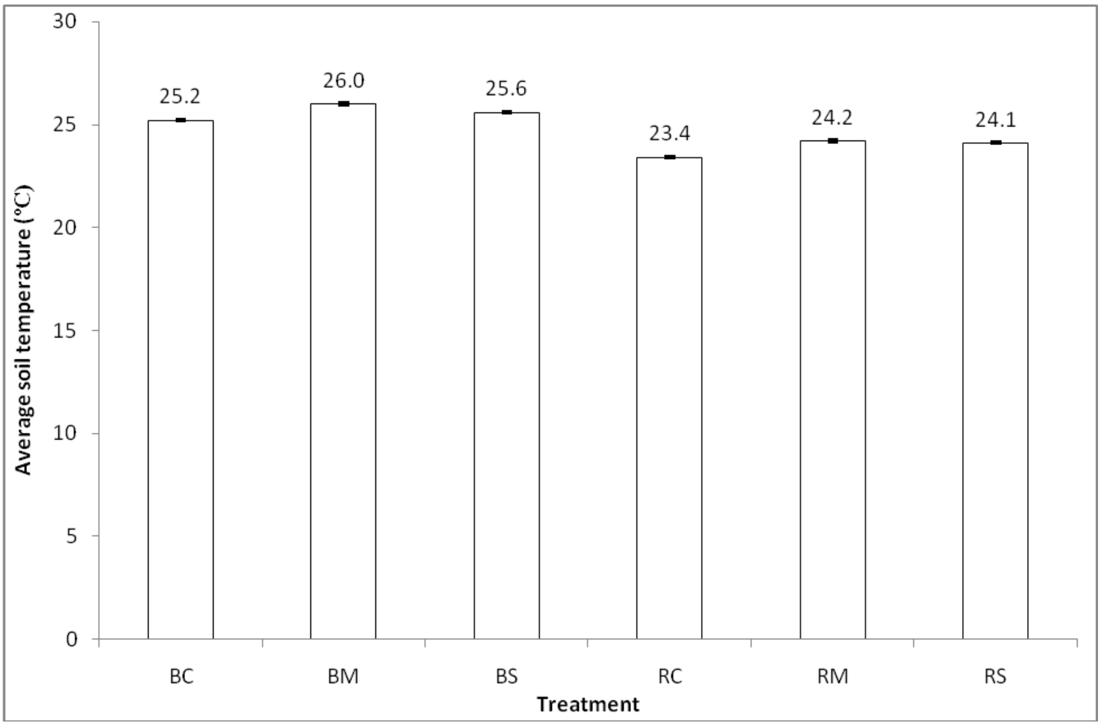

Figure 7. 5 Season-long average soil temperature for the wheat experiment. The letters B and R refer to black Vertisol and red Ferrosol, C, M, and S refer to control (non-aerated), Mazzei air injector venturi, and Seair diffusion system, respectively.

Figure 7.6 shows an illustrative variation in the soil oxygen concentration measured in RS1 and RC2 for three days starting from October 1, 2008. The measurements began at 11:41 am; approximately ten minutes before commencement of the irrigation. The irrigation time for the aerated and control treatments took 52 and 57 minutes, respectively. As can be seen from Figure 7.6, aeration of the irrigation water by Seair resulted in a higher soil oxygen concentration than the control treatment. The average measured soil oxygen content in RS1 and RC2 were 7.19 and 6.91 mg L^{-1}, respectively.

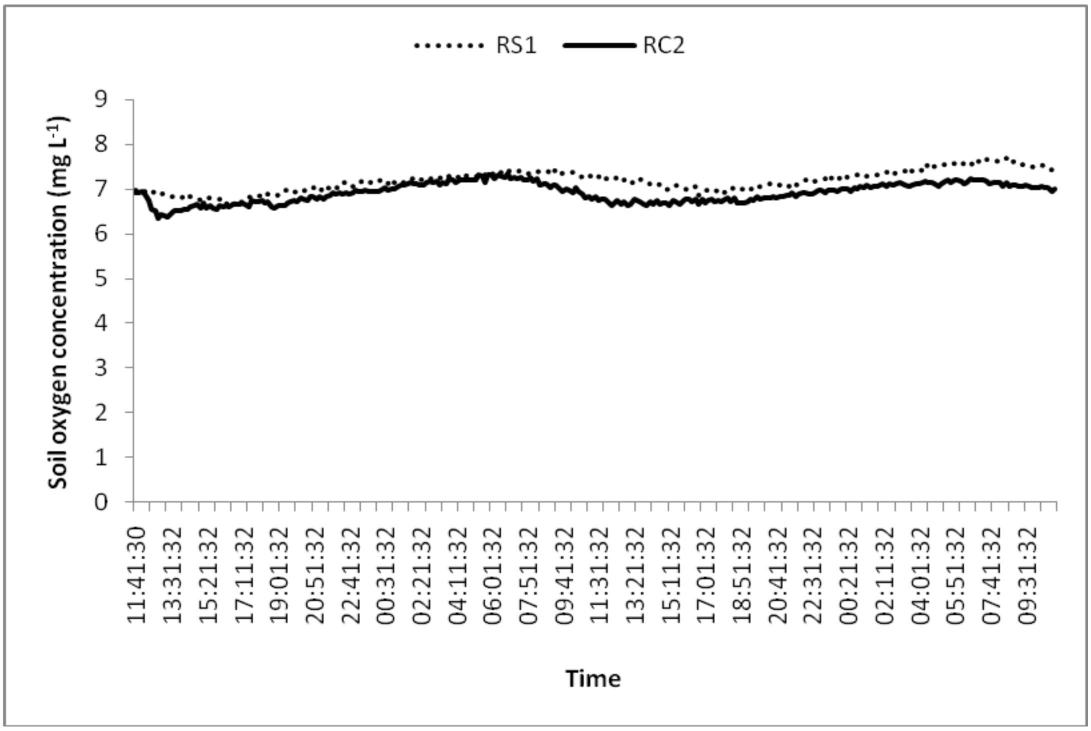

Figure 7. 6 Soil oxygen concentration measured in the first block of red Ferrosol aerated by Seair diffusion system (RS1) and the second block of control (non-aerated) red Ferrosol (RC2.) Irrigation commenced at 11:51 am and finished at 12:43 pm and 12:48 pm for RS1 and RC2, respectively.

The mean emitter air flow rates for the Mazzei and Seair treatments were 0.90 and 0.81 L h^{-1}, respectively. The corresponding Christiansen's uniformity coefficient of the emitter air flow rates for Mazzei and Seair were 21% and 33%, respectively. Spatial distribution of the emitter air flow rates for the aerated treatments presented a non-monotonic trend across the blocks (Figure 7.7). However, the trend of emitter air flow rates across individual blocks was invariably declining (Figure 7.8). The mean air flow rate for the first block of the treatment (i.e. the closest tub to the source of aeration) oxygated by Mazzei air injector was 21% larger

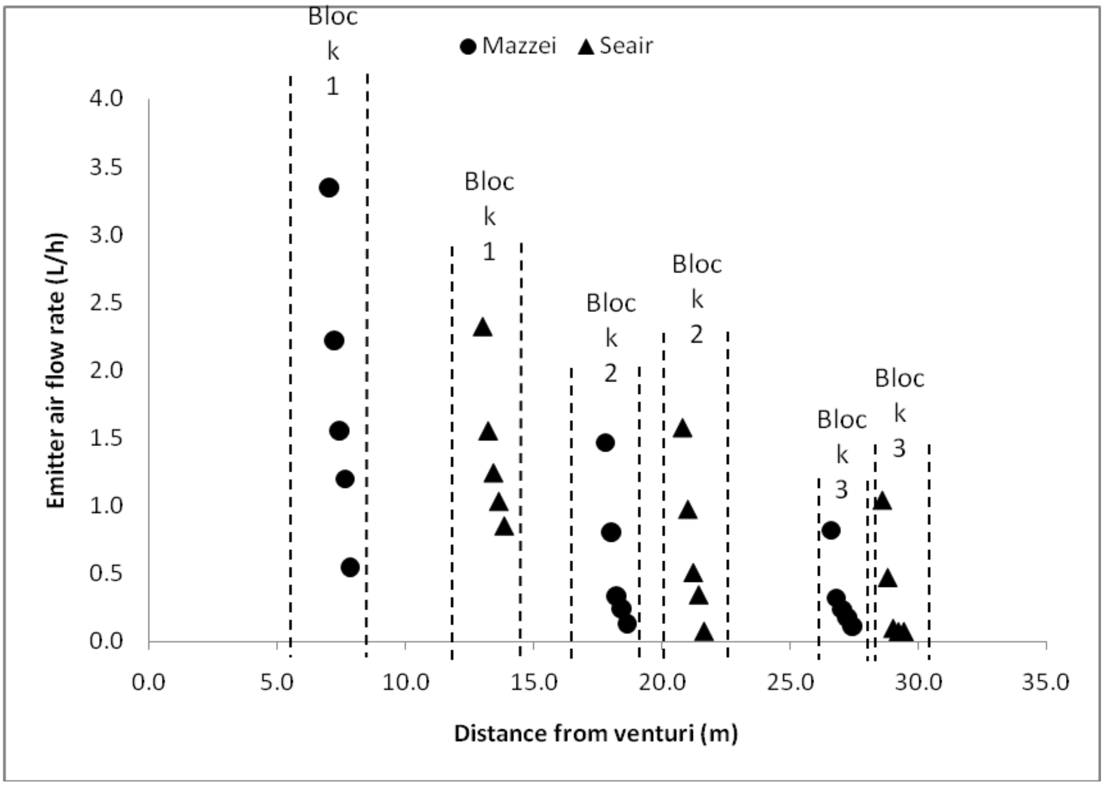

Figure 7. 7 Spatial distribution of emitter air flow rates across the aerated blocks of Mazzei and Seair treatments.

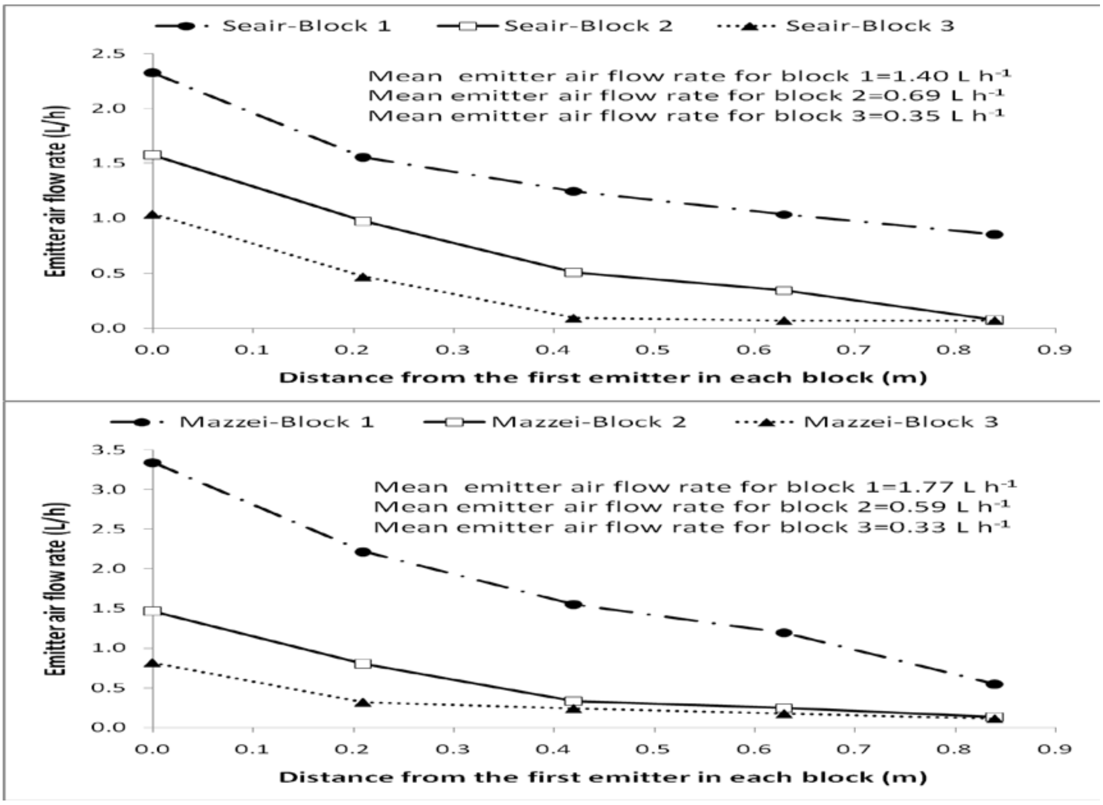

Figure 7. 8 Emitter air flow rates across individual blocks for Mazzei (top) and Seair (bottom) treatments.

than that for the first block of the treatment oxygated by Seair. Nonetheless, the difference in the mean air flow rates from the Mazzei aerated blocks in comparison to those oxygated by Seair were diminished in the second and particularly in the third blocks.

Table 7.2 shows the effect of oxygation and soil type on the crop growth characteristics and wheat yield components. Generally, the highest performance was observed in the Mazzei treatment followed by the Seair, and the least was recorded for the control treatment. However, with the exception of the leaf chlorophyll concentration, all the other parameters presented in Table 7.2 did not significantly differ between the control and the oxygation treatments. As for the leaf chlorophyll concentration, the values recorded for the Seair and Mazzei treatments were 5% and 10% higher than the value measured for the control treatment, respectively. However, only the difference between the Mazzei treatment and the control was significant at 10% level of confidence.

From Table 7.2, it is evident that the leaf chlorophyll concentration in the plants grown on Ferrosol was significantly higher than that for Vertisol. The measured leaf water potential, crop water stress index, and instantaneous water use efficiency for Vertisols were markedly (but not significantly) greater than those in Ferrosols. For the rest of the growth parameters presented in Table 7.2, Vertisols showed significantly better performance than did Ferrosols.

7.4 Discussion

From Table 7.1, the seasonal average soil moisture for Vertisol and Ferrosol was 34.5 and 21 mm H_2O 100 mm^{-1} soil, respectively. The relative difference between the mean soil moisture and the corresponding FC values were 20% and 28%

Table 7. 2 Growth parameters and yield components of wheat under different treatments.

Effects	Treatments	Leaf chlorophyll concentration (SPAD unit)	Leaf water potential (-kPa)	CWSI	WUEi (μmol /mmol H_2O	Number of ears per m^2	Weight of fresh biomass ($g\ m^{-2}$)			Weight of dry matter ($g\ m^{-2}$)		
							Ears	Leaves	Stems	Ears	Leaves	Stems
Oxygation	Control	37.1	1000	0.22	5.96	329.4	727.5	404.7	993.4	260.0	136.1	308.9
	Mazzei	41.0	1040	0.18	6.54	357.1	820.0	479.4	1068.5	289.2	160.2	313.2
	Seair	38.9	1130	0.18	5.96	337.5	777.7	478.8	1037.7	271.0	132.1	322.4
	Average LSD (df = 10)*	**2.3**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
Soil type	Vertisol	37.5	1090	0.21	6.36	383.4	925.6	569.2	1252.3	328.5	194.3	382.5
	Ferrosol	40.9	1040	0.17	5.99	302.2	636.4	351.7	824.1	221.6	93.0	248.6
	LSD (df = 10)	**1.8**	**n.s.**	**n.s.**	**n.s.**	**46.2**	**143.7**	**143.6**	**229.6**	**46.7**	**31.1**	**55.4**

*: LSD, least significant difference; df, degrees of freedom; n.s., not significant.

for the Vertisol and Ferrosol treatments, respectively. The higher soil moisture in the treatments containing Vertisol in contrast to Ferrosol was mainly attributed to the difference in the permeability of these two soil types. Vertisols generally contain 35% or more by weight of clay particles and are classified as a swelling soil with a saturated hydraulic conductivity ranging from 0.1 to 10 mm h^{-1} (Shaw & Yule 1978; Forrest et al. 1985; Bird, Willis & Melville 1996; McKenzie et al. 2004). In contrast to Vertisols, Ferrosols are defined as a non-swelling clay and strongly form aggregates resulting in reportedly extremely high permeability as large as 1000 mm h^{-1} (Bridge et al. 1996; McKenzie et al. 2004). It should be noted that there were no data for soil particle analysis or permeability measurements for either Vertisol or for Ferrosol samples in this experiment. However, it is likely that the relatively higher permeability of Ferrosol resulted in the fast drainage of the gravity water and lower water contents after irrigation events in the treatments with Ferrosol. This is further supported by the relatively higher degree of soil saturation for Vertisol at all the 10 cm depth intervals in comparison with those of the corresponding depths for Ferrosol as presented in Figure 7.4. Evidently, following an irrigation event, a soil of low hydraulic conductivity will retain more moisture in comparison with a soil of high hydraulic conductivity.

The difference in soil temperature between Vertisol and Ferrosol is mainly attributed to the difference in the soil colour. Vertisols (black clay soils) are darker than Ferrosols (red clay soils). They absorb more energy and have a higher temperature, whereas Ferrosols, lighter in colour, reflect more energy and have a relatively lower temperature.

The soil oxygen concentration in the RS treatment was consistently higher than in the RC treatment. However, oxygation of Ferrosol with Seair over the three days of monitoring led only to 4% higher soil oxygen concentration compared to the control. The small difference in the concentration of soil oxygen between the treatments is attributed to two factors: soil temperature and chimney effect. From Figure 7.5, the measured seasonal average soil temperatures at 15 cm depth for RS and RC treatments were 24.1 and 23.4 °C, respectively. The solubility of oxygen in pure water at mean sea level pressure and 23.4 °C is 8.50 mg L^{-1}, whereas at 24.1 °C the oxygen solubility declines to 8.39 mg L^{-1}. Moreover, during irrigation events, air bubbling at the soil surface was often observed in almost all the aerated treatments. This is explained by the relatively high compressibility of air in comparison with water. At atmospheric pressure, air is approximately 16000 times greater than that of water (Goldberg, Raichlen & Forsberg 2001). This allows air bubbles (including microbubbles) to expand in response to decrease in pressure as they are discharged from the emitters. The larger the increase in the diameter of air bubbles, the greater is the lifting force of buoyancy on the bubbles. The shallow placement of emitters facilitated effervescence of the bubbles into air.

The soil oxygen concentration was higher during night time and lower between midday to 1600 h (Figure 7.6). Soil oxygen consumption and carbon dioxide efflux usually increase in the morning as a consequence of increase in the soil temperature, reach a peak at noon to mid-afternoon as the soil temperature increases, and then decline in the afternoon and throughout the night as the temperature declines (Xu & Qi 2001; Bijracharya, Lal & Kimble 2000).

The trend in the distribution of emitter air flow rates with asymmetric connectors for the Mazzei and Seair treatments across the blocks (Figure 7.7) is distinctive from the trend of emitter air flow rates with the same type of connector shown in Figures 3.19-3.22 in Chapter 3. The latter Figures all present a monotonically declining trend in the distribution of emitter air flow rates along an irrigation pipe, whereas the emitter air flow rate distributions in Figure 7.7 show a fluctuating trend. In the Figures 3.19-3.22, the emitters were evenly spaced at 50 cm intervals along a 17 m long irrigation pipe. Hence, the resulting emitter air flow rates presented a monotonic trend. In the wheat experiment, each block (i.e. tub) was oxygated by 20 emitters evenly spaced at about 4 cm intervals, while the distance between the last emitter of a block with the first emitter of the next block ranged between 7 to 10 m, depending on the randomized location of the blocks. The total length of an irrigation pipe in the wheat experiment was about 27 m. Similar to the results obtained from emitters with asymmetric connectors in the previous chapters, the first few emitters in the first block of the aerated treatments delivered larger air flow rates compared to the distal emitters of the first block. The emitters in the aerated treatments delivered $20 \times 2 = 40$ L h^{-1} water and nearly 1.58 L h^{-1} (Figure 7.8) air to the first block. It is likely that delivery of 40 L h^{-1} of water led to a reduction in water pressure which in turn caused expansion in the diameter of the air bubbles. As the two-phase flow reached the second block, the increase in the diameter of the air bubbles together with the turbulence from the asymmetric connectors improved availability of air bubbles to the first few emitters of the second block and hence a rise in the emitter air flow rates (the second blocks in Figure 7.7). The same procedure was repeated for the third block and caused the rise in the emitter flow rates for the third block of the aerated emitters. In contrast to the fluctuating trend in the emitter air flow rate distribution across the aerated blocks, monotonically declining trends in the emitter air flow rates were recorded within individual blocks which are in agreement with the trends presented in the previous chapters.

The calculated CUC for the Seair treatments were larger (i.e. more uniform) than the CUC values calculated for the Mazzei treatments. Quite clearly, the larger air flow rates measured in the Mazzei treatment, which were non-uniformly distributed along the lateral pipe, caused the relatively lower CUC in comparison with the Seair treatments. The inverse relationship between mean air flow rate and CUC in these measurements is in agreement with the data presented in Table 3.1 of Chapter 3. Moreover, water pressure within the diffusion chamber of the Seair was maintained between 82.7 and 103.4 kPa, while the super-aerated water from the chamber was stored in a water tank in which the water surface was in contact with the ambient air. As the pressurized super-aerated water entered into the non-pressurized water container, the drastic drop in water pressure might have promoted a portion of the micro air bubbles to be expelled from water and hence a reduction in the air flow rates for this treatment.

In contrast to the oxygated treatments, plants grown in the control treatment consistently (but not significantly) showed inferior performance. In subsurface drip irrigation, development of a wetting front in the vicinity of the emitters makes the root zone near-saturated. The anaerobic condition lasts for part of the time between irrigation intervals, especially in fine textured soils with low hydraulic conductivity and will adversely affect the plant root functioning (Bhattarai, Pendergast & Midmore 2006). Under prolonged anaerobic conditions within the root zone, oxygen deficiency diminishes the ability of roots to furnish the shoots with water and nutrients (Jackson 1990). Restrained nutrient uptake results in nutrient shortage in shoots which might lead to leaf aging and halt in shoot growth under severe hypoxia/anoxia (Trought & Drew 1980). Clearly, aeration of the root zone will help the root to continue its functioning and the aforementioned symptoms will be alleviated. Data in Table 7.2 indicate a somewhat enhanced performance of wheat in the oxygated treatments in contrast to the control. Despite the improved performance of the oxygated treatments, they did not significantly differ from the control. One possible reason for this outcome could be the small air flow rates delivered to the oxygated treatment. According to Thomson, Atwell & Greenway (1989), the oxygen requirement of wheat roots for optimal growth in well-stirred nutrient solution is at least 0.06 mol O_2 m^{-3}, equivalent to 1.34 L m^{-3}. From Table 7.2, the average emitter air flow rate for the oxygated treatments was nearly 0.86 L h^{-1}. Assuming oxygen constitutes 21% of the air volume and every irrigation event took 45 minutes on average, the approximate volume of oxygen supplied to unit volume of soil in each oxygated tub would be 1.77 L m^{-3}. Although the average oxygen concentration (in soil) supplied to the oxygated treatments appears to be slightly higher than the proposed concentration (in a well-stirred solution) for optimum growth, there is little mixing in soil so the rate of oxygen diffusion to roots would be a major restriction to root growth rather than absolute concentrations in the bulk solution (Dracup, Belford & Gregory 1992). Moreover, air bubbling from the soil surface was often observed for almost all the aerated treatments during irrigation events, indicating loss of part of the oxygen supplied to the root zone. Owing to the above reasons, it is likely that the oxygen diffusion rate to the roots during irrigation events was sub-optimal and this led to the non-significant difference between the control and the oxygated treatments. For the Mazzei treatment, if a venturi model 484 were used instead of the venturi model 384, the rate of air flow for the same pressure differential used in this experiment would be increased from 48.2 L h^{-1} to 143.4 L h^{-1}, provided that the minimum motive water flow rate could be accordingly increased from 429 L h^{-1} to 734 L h^{-1} in the line (Mazzei Injector Corporation, n.d.). Technically, in a recirculating irrigation system, motive water flow rate could be increased without any limitation. To improve air supply in the Seair treatment, if the super-aerated water from the diffusion chamber were stored in a pressure vessel with at least the same pressure as in the diffusion chamber, it would be more likely that more air could be supplied to the plant roots oxygated by the Seair system. Moreover, a deeper placement of emitters (e.g. 20 cm) could possibly prevent surface air bubbling, thereby improving the efficiency of oxygation.

Table 7.2 revealed that with the exception of the leaf chlorophyll concentration, the growth parameters and yield components were better for the Vertisol compared with the Ferrosol. Iron is an essential element for oxidation and reduction of sulphates and nitrates, electron transfer, protein and chlorophyll formation, photosynthesis, and other enzyme activities (Rakkiyappan, Thangavelu & Radhamani 2002). Moreover, insufficient soil iron content impairs chlorophyll biosynthesis and chloroplast development in both monocotyledonous and dicotyledonous species (Ishimaru et al. 2007). In contrast to Vertisols, Ferrosols are very rich in free iron oxide contents ranging from 7 to 18% (Isbell 1994; Vervoort, Cattle & Minasny 2003) and this was most likely responsible for the higher chlorophyll content on the Ferrosol.

Nevertheless, the plants grown on the Vertisol significantly outperformed those on the Ferrosol. This is attributed to two factors: the relatively richer nutrient status of the Vertisols in comparison to the Ferrosols, and the relatively high permeability of Ferrosols in contrast to Vertisols. The dominant clay type in black Vertisols is smectite (Bridge et al. 1996) with a high cation exchange capacity (CEC) in the range of 80-150 meq 100 g^{-1} (Velde 1995). The CEC is defined as the degree to which a soil can adsorb and exchange cations. Hence, it is an indicator of the degree of soil fertility. In contrast to the black Vertisols, the major clay type in the red Ferrosols is kaolinite and gibbsite (Isbell 1994) with a relatively low CEC ranging from 3-15 meq 100 g^{-1} (Donn, Menzies & Rasiah 2004; Irvine & Reid 2001; McKenzie et al. 2004; Velde 1995). Furthermore, as mentioned at the beginning of this section, the high permeability of Ferrosols allowed for fast drainage of the excess water during and after irrigation events and consequently nutrient leaching from the root zone. Although no measured data were available on soil permeability, and soil or drainage water nutrient content, it is likely that access to relatively more nutrients in the black Vertisols in comparison to the red Ferrosols led to enhanced plant performance in terms of number of ears, instantaneous water use efficiency, and weight of fresh and dry ears, leaves and stems.

7.5 Conclusions

Plant growth and yield components were strongly affected by the soil type. In contrast to Vertisols, plants grown in Ferrosols with reportedly higher permeability (associated with more nutrient loss through deep percolation) and lower CEC showed inferior performance. However, the higher iron content in Ferrosols in comparison to Vertisols resulted in higher leaf chlorophyll content in the plants grown in the former soil type.

Oxygation of wheat plants by means of the Mazzei air injector venturi as well as Seair diffusion system consistently resulted in enhanced, but not always significantly so, performance of the oxygated plants in contrast to the control. However, owing to the air bubbling from the soil surface during irrigation events and the sub-optimal level of oxygen concentration supplied by the aeration systems, the outcomes did not significantly differ from the control. Deeper placement of the emitters (e.g. at 20 cm) will possibly prevent air bubbling from the soil surface and lead to availability of more oxygen to the root zone. Furthermore, use of microdrip emitters of very low water flow rates (i.e. less than 0.5 L h^{-1}) instead of the conventional emitters (such as the 2.0 L h^{-1} ones used in this experiment) will evidently increase the oxygation time and hence aeration time will be accordingly increased without a remarkable decrease in the emitter air flow rates (see section 3.4.1.1 in Chapter 3). It should be noted that any reduction in the emitter water flow rate will result in subsequent reduction in the water motive flow rate from the venturi. Hence, this solution (replacing a conventional emitter with a microdrip one) is feasible only for a recirculating irrigation system where the excess motive flow rate can flow back to the irrigation tank; not for a dead end irrigation system. When considering improvements in efficiency of the Seair treatments, storage of the super-aerated water from the diffusion chamber into a pressure vessel at least of the same pressure as in the diffusion chamber (i.e. 12-15 psi) might prevent loss of air bubbles from the water tank into the air and consequently lead to the availability of more air to the plant roots in these treatments.

Chapter 8: The response of vegetable soybean to frequent application of surfactant in oxygation

ABSTRACT

The objective of this experiment was to evaluate the effect of aerated or non-aerated irrigation water with or without frequent (daily) application of a non-ionic surfactant (BS 1000™) at a concentration of 2 ppm in the irrigation water on growth parameters of vegetable soybean (*Glycine max* L.) grown on two soil types: Vertisol and Ferrosol.

Soil oxygen concentration in the aerated treatments was 15-27% higher in comparison to that in the controls. Aerated water, Vertisol, and surfactant independently enhanced the growth parameters, but strong effects were observed from the soil type.

The uniformity of emitter air flow rate distribution, expressed by Christiansen's uniformity coefficient (CUC), along the lateral pipe for the treatments without surfactant was very low (CUC = 5%); with the first block receiving the highest emitter air flow rates followed by the second, the third , and the fourth block. In contrast to the aerated treatments without surfactant, addition of surfactant markedly enhanced the distribution uniformity of emitter air flow rates (CUC = 81-85%) but accordingly dropped off the emitter air flow rates across the blocks. The high emitter air flow rates in the first block of the treatments without surfactant (~ 8 L h^{-1}) notably increased the crop yield compared to the control, whereas the emitter air flow rates in the first block of the treatments with surfactant were too low (0.62-0.67 L h^{-1}) to considerably increase the plant performance. Generally, addition of surfactant to water in the open-end drip irrigation system enhanced the plant

performance, however the emitter air flow rates were too low to make a significant difference in the plant performance.

8.1 Introduction

Anaerobic conditions resulting from excessively heavy rainfall, flooding, and poor drainage are climatic factors that may limit growth of soybean (Stanley, Kaspar & Taylor 1980; Scott et al. 1989; Oosterhuis et al. 1990; Russell, Wong & Sachs 1990). There are many factors that can affect the extent of yield loss in waterlogged areas including growth stage, soil type, cultivar, and duration of soil saturation.

As soil becomes saturated, soil air will be substituted with water, limiting oxygen diffusion through the soil (Pezeshki 1994). Plant roots and soil biota consume the remaining oxygen quickly through respiration. Once soil becomes deprived of oxygen, plants may suffer reduced photosynthesis and respiration, reduction in uptake of minerals, impaired growth regulator relationships, reduced growth rates, stomatal closure, leaf wilting, chlorosis, and potentially death (Helms et al. 2007).

Subsurface drip irrigation provides opportunities for enhancing water use efficiency and alleviating the negative environmental effects of irrigation (Bhattarai, Midmore & Pendergast 2008). Goorahoo et al. (2002) employed an innovative technique for concurrent supply of the bell pepper rhizosphere with water and air via coupling a venturi air injector immediately following the irrigation pump. They found 39% increase in the weight, and 33% increase in number of bell peppers in the aerated treatment compared with the control. However, the positive effect of aerated water showed a declining trend along the crop row. This was in agreement with the results mentioned in Chapters 3, 6, and 7 of this thesis for the distribution of emitter air flow rates as well as plant performance along lateral pipes. One solution to improve the uniformity of emitter air flow rates is through the reduction of water surface tension thereby reducing the diameter of air bubbles and accordingly increasing the number of the air bubbles, which in turn leads to the availability of more air bubbles to remote emitters. This can be achieved by addition of surfactants to irrigation water.

Surfactants (surface active agents) are amphiphilic molecules containing a hydrophobic portion and a hydrophilic (polar) head group. With respect to the type of charge on their polar head group, surfactants are generally classified into four classes as anionic, non-ionic, cationic, and zwitterionic (Lee et al. 2002). Surfactants have been shown to increase water infiltration into the soil, seedling germination and establishment, and to decrease soil erosion on water repellent soils (Osborn et al. 1967; Osborn, Letey & Valoris 1969). The objective of this experiment was to evaluate the effect of aerated or non-aerated irrigation water with or without frequent (daily) application of a nonionic surfactant (BS 1000™) on growth parameters of vegetable soybean (*Glycine max* L.) grown on two soil types: Vertisol and Ferrosol.

8.2 Materials and Methods

The pot experiment was conducted at the same location as in Chapter 4, on vegetable soybean (*Glycine max* L.) variety ‘Bunya’ from November 2008 until February 2009. The experiment was laid out as a 2×2×2 factorial randomized complete block design, replicated four times with eight treatment combinations. The treatments consisted of soil type, use of surfactant in the irrigation water and aeration of the irrigation water. The two soil types were black cracking clay soil named black Vertisol, and red clay soil named red Ferrosol (Isbell 1996). Half of the containers were filled with 28 kg of Vertisol and the other half were filled with 29 kg of Ferrosol. A vibrator was used to ensure uniform soil porosity between pots with a soil type before imposing the treatments, and the field capacity for Vertisol and Ferrosol was 43 and 29 mm H_2O 100 mm^{-1} soil, respectively. The bulk density of the Vertisol and the Ferrosol was maintained at 1.3 and 1.4 g cm^{-3}, respectively.

Alcohol alkoxylate, a biodegradable (i.e. relatively safe to the environment) and non-ionic (i.e. no interference/interaction with fertilizers) surfactant, and available in pure form, was used as an experimental factor in this experiment to enhance the uniformity of air bubble distribution along the irrigation pipe. It was diluted to 150 ppm (C_i) before injection into the irrigation system and was injected at a rate of 10.3 L h^{-1} into the irrigation pipe. The final concentration (C_f) of surfactant in the treatment combinations which received surfactant was 2 ppm resulting from a water flow of 810 L h^{-1} in the irrigation pipe. Surfactant was injected into the irrigation system by means of a Netafim™ chemical injector venturi[1] model F3/4-0.9. The inlet and outlet pressures across the surfactant injector venturi were 283 and 200 kPa (41 and 29 psi), respectively.

The eight experimental treatments were designated as BSA, BPA, BSC, BPC, RSA, RPA, RSC, and RPC, where the letters B and R refer to soil type: black Vertisol and red Ferrosol, S, and P refer to with and without surfactant, and A, and C refer to aerated and non-aerated (control) irrigation water, respectively.

In each block, a treatment combination comprised of four 21-L contiguous white containers each accommodating three plants. On November 19, 2008, nine seeds were sown per container. Twelve days after sowing (DAS) when the plants had

[1] The use of product names in this research is not an endorsement of the company's product. These names are mentioned here primarily for the purpose of letting readers know where the relevant materials can be obtained.

produced four true leaves, they were thinned to three plants per container and the treatments were imposed. Each container, of 40 cm height and 26 cm diameter, was perforated at the base to facilitate drainage of excess water. A cloth sieve was placed at the bottom of each container to prevent soil particles from washing out, without interfering with the drainage of excess water. Moreover, the interior side of the containers was covered by black plastic sheets to prevent light from changing the soil biosphere conditions. Totally, one hundred and forty four containers spaced 60 cm between rows and 26 cm within rows were used with sixteen acting as the two guard rows (Figure 8.1). Each container was fitted via asymmetric connectors with a single Netafim™ model 'PCJ' 1.2 L h^{-1} pressure compensated pot dripper with 50-400 kPa (7-58 psi) operating pressure. The emitters were placed 15 cm below the soil surface. A Netafim™ venturi model F3/4-0.9 was used for injection of air into the irrigation system. The inlet and outlet pressures across the air injector venturi were maintained at 200 and 69 kPa (29 and 10 psi), respectively. To prevent the air bubbles from bypassing, a 19 mm ID single pipe similar to the one described in Chapter 6 was used for irrigation of each treatment. The end of the irrigation pipe was left unplugged and was placed into a drain. The pressure at the end of the irrigation pipes was maintained at 62 kPa (9 psi).

The nutrient requirements of the crop were supplied as in Chapter 4. Fertigation was achieved at the rate of 1 g L^{-1} resulting in application of 8.1 g fertilizer per pot per day. To account for different uptake rates of water between treatments, at times irrigation was applied without fertigation to ensure that all plots received the same amount of nutrients.

Oxygen concentration in the soil was measured using PSt3 oxygen-sensitive fibre optic mini-sensors with a Fibox-3 oxygen meter (PreSens GmbH, Germany). It

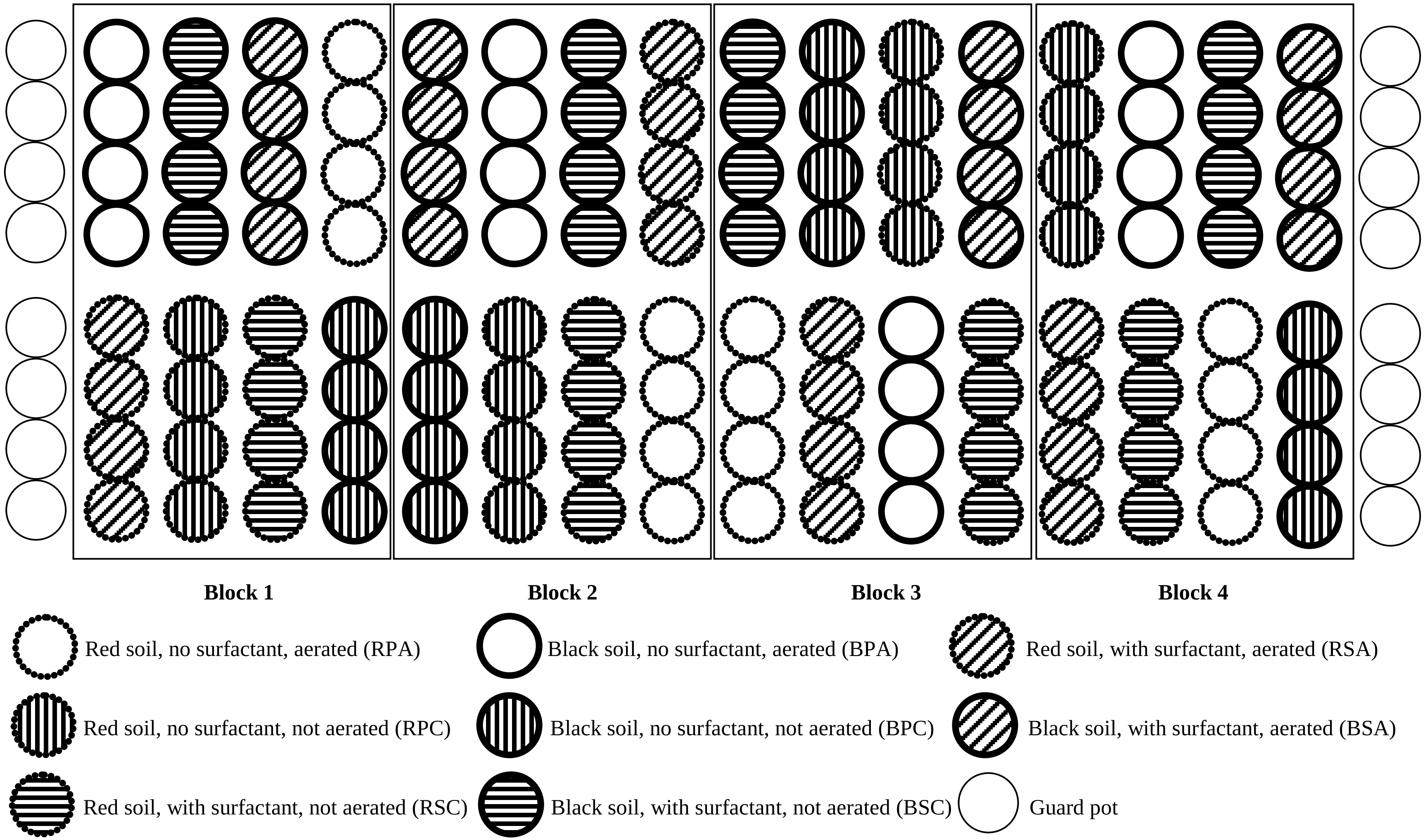

Figure 8. 1 Experimental layout. Eight treatments are replicated four times, with each replicate consisting of four pots.

is an optical sensor that measures the oxygen concentration in the gaseous and liquid phase. The measurements were undertaken at 36, 44, and 46 DAS. Four days before oxygen measurement, the sensor was inserted 15 cm deep and 10 cm from the emitter in the centre of the first bordered pot in the first block of each treatment.

All treatments were irrigated daily for seven hours and the injection rate for surfactant, and for air, were checked twice during each irrigation event to avoid any unforeseen change. Duration of irrigation was the same for all the treatments, hence they received the same irrigation rate. Soil moisture was measured on five occasions (15, 31, 52, 67, and 83 DAS) before and immediately after cessation of irrigation over the growing season in one pot per experimental plot by means of a calibrated Micro Gopher (Soil Moisture Technology Pty Ltd, Australia) capacitance sensor. Canopy light interception was measured 41 DAS. To determine the light interception, photosynthetically active radiation (PAR) was measured above and below the crop canopy between 1100 h and 1400 h with an AccuPAR ceptometer (Decagon USA). In each plot, the ceptometer was placed at right angles to the crop row and two readings were taken and then averaged; each consisting of one reading above the canopy and five readings beneath the canopy. Percent canopy light interception was calculated as the relative difference between PAR above and beneath the canopy: Light Interception (%) = $[(PAR_{above} - PAR_{below}) / PAR_{above}] \times 100$. For each treatment, totally four readings were recorded and averaged.

For the aerated treatments (with or without surfactant), emitter water and air flow rates were measured using the same procedure as described in sub-section 3.2.1.1 of Chapter 3. Using 0.55 L plastic bottles for water collection and a stop watch for keeping the time, water flow rates from the emitters were measured three times and then averaged. To collect air bubbles from each emitter, a pot filled with water with an inverted 0.55 L plastic bottle fully immersed into the pot was used. The immersed bottle was carefully emptied of air bubbles prior to starting the measurements. When an emitter was put into the inverted bottle, the discharged air bubbles displaced water and accumulated in the inverted bottle. The volume of the discharged air bubbles was equal to that of the displaced water (ignoring the volume of the suspending micro air bubbles in the sampled water). The air flow rate was calculated as the volume of the air (the difference between the volume of water remaining in the bottle and the full volume of the bottle) divided by the time period when air bubbles were collected. The volume of water was measured with a 1000 mL measuring cylinder.

In addition to air flow rate, efficiency of air bubble delivery, and Christiansen's uniformity coefficient (CUC) of the air flow rates were measured. Efficiency of air bubble delivery (AE), expressed as a percentage, is defined as the ratio of the sum of air flow rates discharged by the emitters to the air flow rate supplied at the outlet of the air injector venturi. To calculate the sum of air flow rates from the emitters, first the taps on riser tubes (intermediators between the connectors and the emitters) were shut so that no water or air passed through the emitters. Hence, the entire air volume supplied by the venturi could be collected at the end of the irrigation pipe. To collect the air bubbles, the end of the pipe was put into a tank full of water. A 5000 mL measuring cylinder was immersed into the water while inverted. Prior to putting the end of the pipe into the jug, care was taken to vacate air bubbles from the jug. At the end of a time period, the bottom of the measuring jug was partially lifted above the water surface in the tank in order to read the volume of the collected air. The procedure was repeated three times and the measurements averaged. Next, all the taps were opened and air flow rate at the end of the pipe was again measured with the same procedure as above, for three times and then averaged. The difference between these average values indicates the cumulative air flow rates discharged from the emitters.

CUC was used as a measure of uniformity of air flow rate distribution along the irrigation pipe. It was calculated by the following equation:

$$CUC = \left(1 - \frac{D}{M}\right) \times 100 \tag{8.1}$$

where:

CUC = Christiansen's coefficient of uniformity (%)

D = average of the absolute values of the deviation from the mean air flow rates

$$= \frac{1}{n}\sum_{i=1}^{n}\left|X_i - M\right| \tag{8.2}$$

X_i = emitter air flow rate of the *i*th emitter

n = number of measured flow rate values

M = average of air flow rate values

$$= \frac{1}{n}\sum_{i=1}^{n}X_i \tag{8.3}$$

To evaluate the sufficiency of air supply to the root zone of the treatments, simple calculations similar to those described in Chapter 6 were performed with five amendments as following: i) the volume of water delivered to each pot was determined based on the constant irrigation time (7 hours, in this experiment) and the measured average emitter water flow rate for each treatment; ii) the soil air porosity at the end of an irrigation event was estimated based on the total soil porosity and the season-long average soil moisture measured after cessation of irrigation; iii) oxygation time was constant (7 hours); iv) the average root oxygen consumption was assumed to be 200 μmol O_2 g^{-1} dry weight of root per hour at 25 ºC (Grable 1966; Walsh 1995); and v) since only the dry weight of above ground biomass was available, an average root:shoot ratio of 0.171 determined by Bhattarai (2005, p. 163) for soybean was used for estimation of the weight of dry roots.

For each treatment, the yield and yield components including number of nodes, leaves, marketable pods (i.e. pods containing two or more seeds), total number of pods, and dry weight of leaves, stems, above ground biomass, marketable pods, and total pods were recorded on a per plant basis from the central two pots of each plot. The collected data were subject to the general analysis of variance (ANOVA) using LSD for mean separation ($P<0.10$) following GenStat version 10.1.

8.3 Results

The seasonal average soil moisture before irrigation events for each treatment is presented in Figure 8.2. Generally, the average soil moisture in treatments with Vertisol was above the field capacity (FC), with BSA being the closest to the FC, followed by BSC, BPA, and BPC. The average soil moisture in the treatments with Vertisol was approximately 6% above the FC. In the treatments with Ferrosol, the average soil moisture was somewhat less than the FC, with RSA being the driest, followed by RSC, RPA, and RPC. On average, the soil moisture in the treatments with Ferrosol was 12% below the FC.

Figures 8.3, 8.4, and 8.5 present data on soil oxygen concentration for BPA, BPC, RSA, RSC, BSA and BDC. Due to a problem with the Fibox, measurement of soil oxygen concentration for RPA and RPC was not obtained. Clearly, for all relevant comparisons, the soil oxygen concentration in the aerated treatments was higher than the corresponding control. During irrigation, the soil oxygen

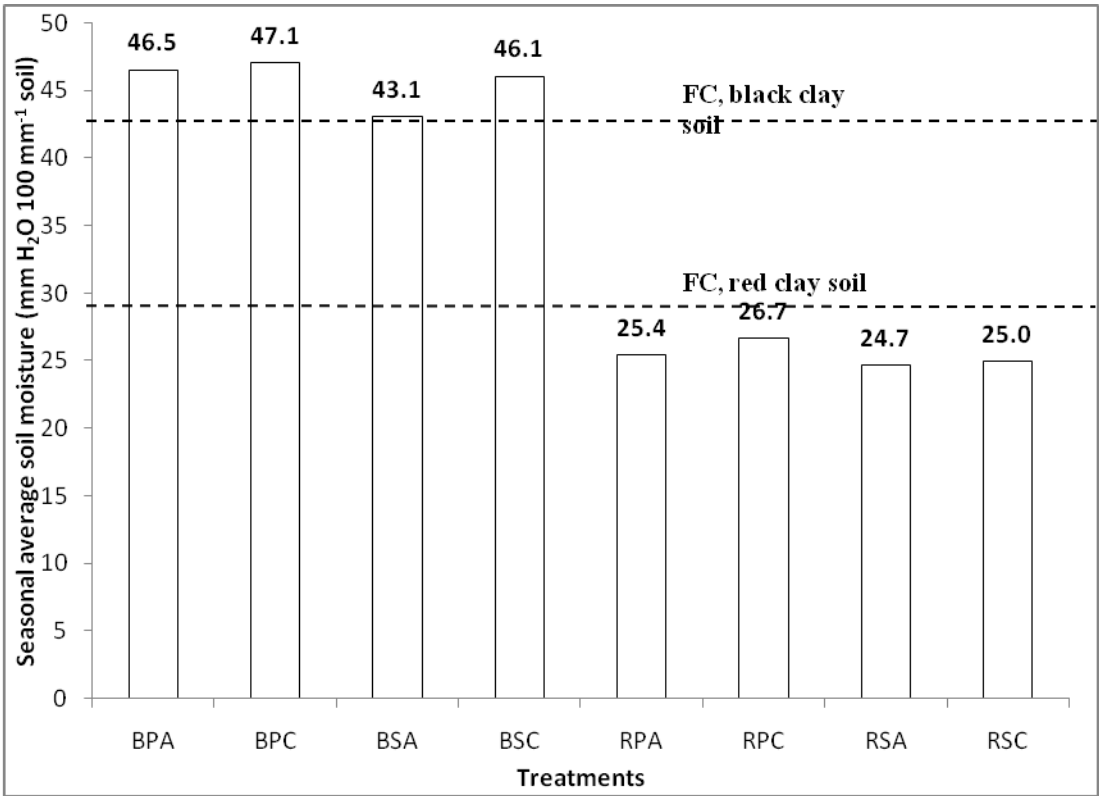

Figure 8. 2 Soil water content (before irrigation), averaged over the growing season. Abbreviations as in Figure 8.1.

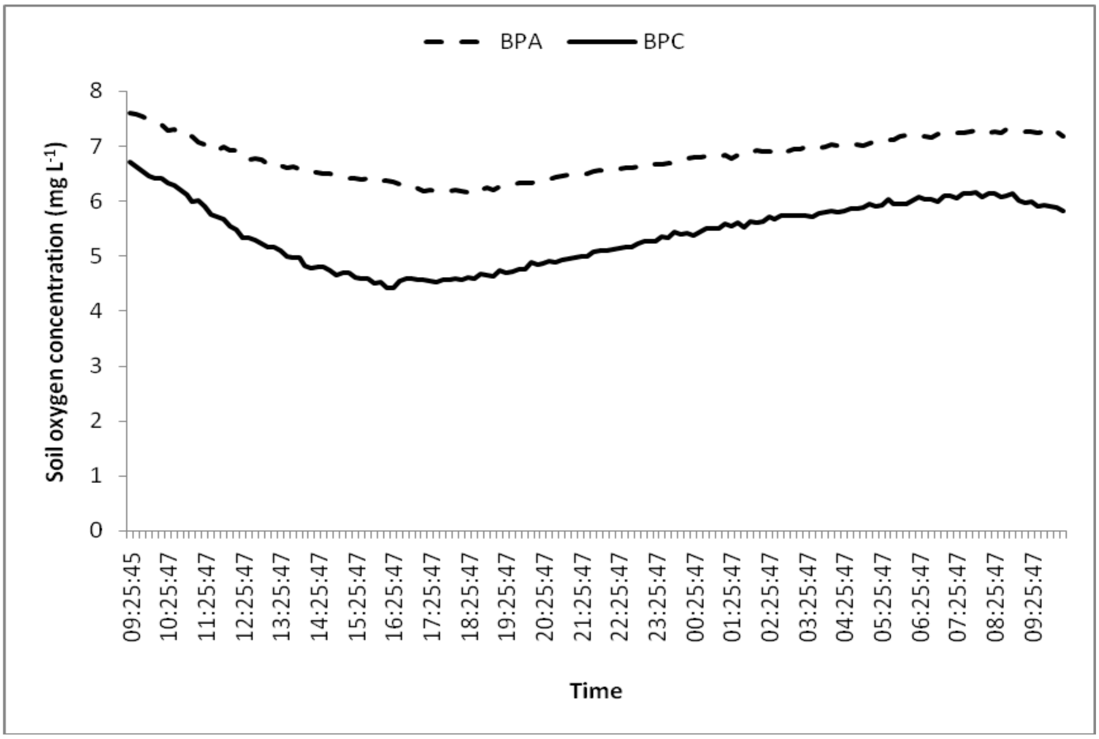

Figure 8. 3 Variation of soil oxygen concentration in the Vertisol, no surfactant, aerated treatment (BPA; dotted line) and in the Vertisol, no surfactant, not aerated treatment (BPC; solid line); irrigation started at 0915 h and stopped at 1615 h on December 25 , 2008 (36 DAS).

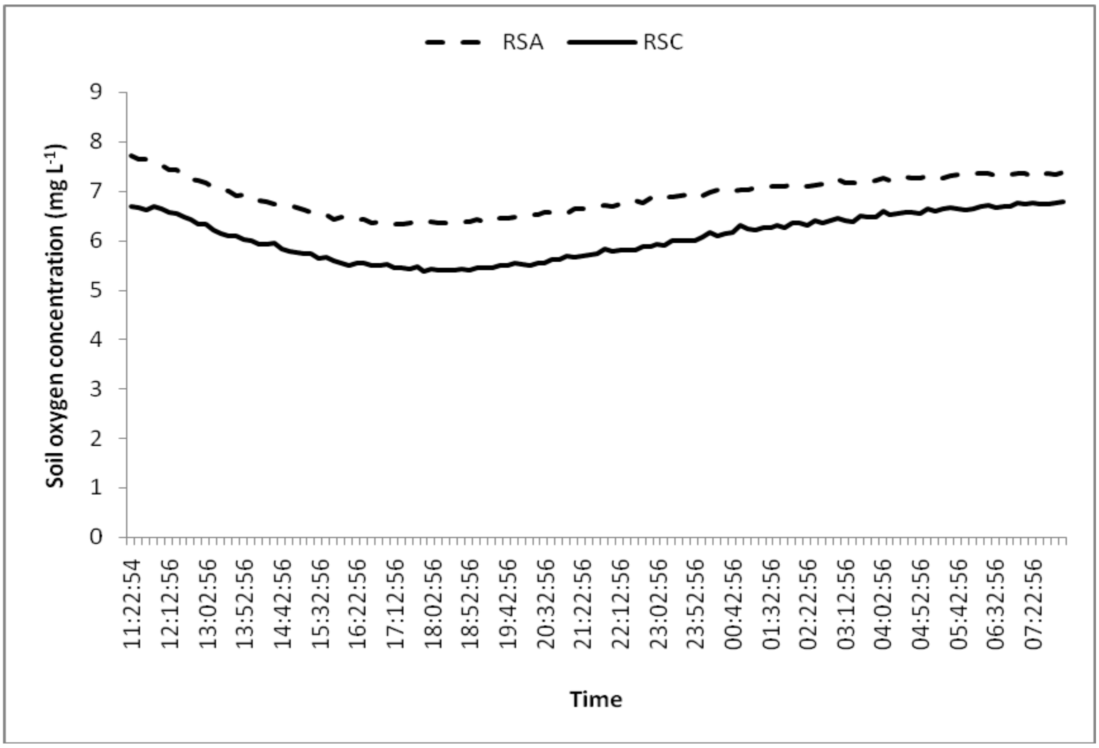

Figure 8. 4 Variation of soil oxygen concentration in Ferrosol, with surfactant, aerated treatment (RSA) vs. Ferrosol, with surfactant, not aerated treatment (RSC); irrigation started at 1115 h and stopped at 1815 h on January 2, 2009 (44 DAS).

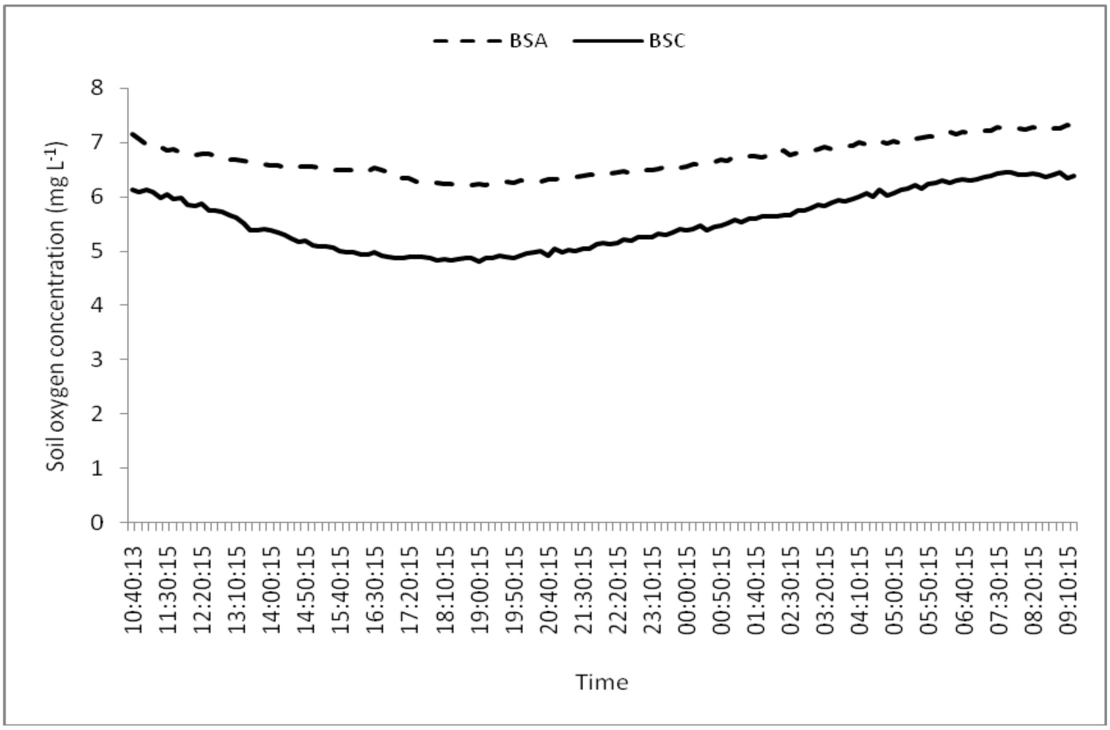

Figure 8. 5 Variation of soil oxygen concentration in Vertisol, with surfactant, aerated treatment (BSA) vs. Vertisol, with surfactant, not aerated treatment (BSC); irrigation started at 1030 h and stopped at 1730 h on January 4, 2009 (46 DAS).

concentrations were greater in the aerated than in the control treatments by 27%, 15%, and 23%, respectively (Figures 8.3, 8.4, and 8.5).

The average of emitter water flow rates measured for the aerated treatment without surfactant was 8% less than the nominal emitter water flow rate (1.2 L h^{-1}), whereas that for the aerated treatment with surfactant did not differ from the nominal emitter water flow rate (Table 8.1). The t-test showed a significant difference between the mean of emitter water flow rates of the treatments with or without surfactant at P<0.10.

Table 8. 1 Average emitter water flow rates (in L h^{-1}) across the blocks of the aerated treatments: with or without surfactant.

Block No.	Aeration without surfactant	Aeration with surfactant
1	0.7	1.2
2	1.1	1.2
3	1.2	1.2
4	1.2	1.2
Mean	1.1	1.2
t^{*}_{14}	2.287	

*The critical value of t_{14} for P<0.10 is 1.761.

The mean of emitter air flow rates and the corresponding efficiency of air bubble delivery (AE) and CUC across the aerated treatment are presented in Table 8.2. For this treatment, a declining trend in the rates of emitter air flow was observed with distance from the air source; the first block received the highest air flow rate and the fourth block the lowest. The efficiency of air bubble delivery (AE) and the mean of emitter air flow rates for the aeration treatment without surfactant were 95% and 3.27 L h^{-1}, respectively. The corresponding Christiansen's uniformity coefficient

(CUC) for the emitter air flow rates was 5%. In contrast to the aerated treatment without surfactant, the distribution of air flow rates across the blocks of the aerated treatment with surfactant (Table 8.2) was more uniform. The CUC for emitter air flow rates was 85%, and the corresponding efficiency of air bubble delivery and average of emitter air flow rates were approximately 25% and 0.55 L h^{-1}, respectively. Addition of surfactant significantly reduced the average emitter air flow rate and efficiency of air bubble delivery at $P<0.10$, but markedly enhanced the CUC.

Table 8. 2 Average emitter air flow rates (in L h^{-1}), efficiency of air bubble delivery (AE), and Christiansen's uniformity coefficient (CUC) across the blocks of the aerated treatments: with or without surfactant.

Block No.	Aeration without surfactant	Aeration with surfactant
1	8.72	0.64
2	3.39	0.56
3	0.73	0.54
4	0.25	0.47
Mean	3.27	0.55
t^*_{14}	2.138	
AE (%)	95	25
t^*_{8}	72.932	
CUC (%)	5	85

*The critical value for t_{14} and t_8 at $P<0.10$ is 1.761and 1.860, respectively.

Table 8.3 shows data and comparisons between means at $P<0.10$ for canopy light interception (LI), the number of nodes, leaves, marketable, and total pods per

Table 8. 3 The effect of aeration, surfactant, soil type, and their interactions on the canopy light interception (LI), number of nodes, leaves, marketable, and total pods per vegetable soybean plant[*].

Variables	Levels	LI (%)	Nodes $plant^{-1}$ (#)	Leaves $plant^{-1}$ (#)	Marketable pods $plant^{-1}$ (#)	Total pods $plant^{-1}$ (#)
Aeration	Aerated	90.9	12.98	20.86	60.5	75.9
	Control	90.5	12.72	21.76	60.2	75.8
	LSD (df = 21)	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
Soil type	Black	89.7	13.87	21.25	65.7	77.5
	Red	91.7	11.82	21.37	55.0	74.3
	LSD (df = 21)	**1.3**	**0.36**	**n.s.**	**6.0**	**n.s.**
Surfactant	With surfactant	90.9	12.95	21.40	61.7	78.1
	Without surfactant	90.5	12.75	21.23	59.0	73.6
	LSD (df = 21)	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
Aeration× Soil type	Aerated×Black	89.4	13.96	21.27	66.5	78.0
	Aerated×Red	92.4	12.00	20.46	54.4	73.9
	Control×Black	90.0	13.79	21.23	64.9	77.0
	Control×Red	91.0	11.65	22.29	55.6	74.6
	LSD (df = 21)	**1.9**	**0.51**	**n.s.**	**8.50**	**n.s.**
Aeration× Surfactant	Aerated×with Surfactant	89.5	12.96	20.69	59.2	74.9
	Aerated×without Surfactant	92.2	13.00	21.04	61.7	76.9
	Control×with Surfactant	92.2	12.94	22.10	64.2	81.4
	Control×without Surfactant	88.8	12.50	21.42	56.3	70.3
	LSD (df = 21)	**1.9**	**n.s.**	**n.s.**	**n.s.**	**10.2**
Soil type× Surfactant	Black×with Surfactant	89.2	13.92	21.02	64.5	76.6
	Black×without Surfactant	90.1	13.83	21.48	67.0	78.4
	Red×with Surfactant	92.5	11.98	21.77	58.9	79.7
	Red×without Surfactant	90.9	11.67	20.98	51.1	68.8
	LSD (df = 21)	**1.9**	**0.51**	**n.s.**	**8.5**	**10.2**
Aeration×Surfactant× Soil type	Aerated×with Surfactant×Black	87.5	13.92	21.04	63.3	74.8
	Aerated×without Surfactant×Black	91.2	14.00	21.50	69.7	81.2
	Aerated×with Surfactant×Red	91.5	12.00	20.33	55.1	75.1
	Aerated×without Surfactant×Red	93.2	12.00	20.58	53.8	72.7
	Control×with Surfactant×Black	91.0	13.92	21.00	65.6	78.4
	Control×without Surfactant×Black	89.0	13.67	21.46	64.2	75.5
	Control×with Surfactant×Red	93.5	11.96	23.21	62.8	84.3
	Control×without Surfactant×Red	88.5	11.33	21.37	48.4	65.0
	LSD (df = 21)	**2.6**	**0.72**	**n.s.**	**12.0**	**14.5**

[*]: $P<0.10$

plant. Vertisol, addition of surfactant, and aerated water, independently enhanced the plant performance, with the influence of these factors decreasing in the order listed. However, only the number of nodes and marketable pods for the Vertisol were significantly higher than those for the Ferrosol whereas canopy light interception (LI) in the Ferrosol differed significantly from those measured in the Vertisol. All the treatments irrigated with surfactant consistently produced higher yields than those irrigated with water alone. Nonetheless the differences were not significant.
The effect of the experimental factors as well as their interactions on the dry weight of leaves, stems, above-ground biomass, marketable and total pods per plant are shown in Table 8.4. Aeration barely increased the weight of marketable and total pods. The weights of stem as well as marketable pods of the plants grown on the black Vertisol were significantly heavier than those grown on the red Ferrosol. Plants which received surfactant water were consistently heavier than those irrigated without surfactant. Nevertheless, the difference again was not significant.

Based on the average soil moisture after cessation of irrigation (Figure 8.6) and the other factors mentioned in section 8.2, the estimated time for consumption of the calculated available oxygen by the plant roots is presented in Figure 8.7. Clearly, there was very little supply of oxygen available to plant roots for all the treatments. The longest estimated time for oxygen consumption was calculated for the aerated treatments irrigated with water alone (RPA and BPA), while the shortest time was computed for the control treatments with Vertisol (BPC and BSC).

Due to the higher air flow rate in the first block of all the aerated treatments, comparing the first block of an aerated treatment with the corresponding non-aerated treatment can help to effectively explore the effect of maximum root zone aeration on the yield components. The relative difference between the yield components from

Table 8. 4 The effect of aeration, surfactant, soil type, and their interactions on the weight (g plant^{-1}) of dry leaves, stems, above ground biomass, marketable, and total pods*per vegetable soybean plant.

Variables	Levels	Leaves	Stems	Above ground biomass	Marketable pods	Total pods
Aeration	Aeration	15.73	11.96	67.2	35.73	39.5
	Control	16.45	12.37	68.2	35.59	39.4
	LSD (df = 21)	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
Soil type	Black	15.96	13.03	69.2	38.02	40.7
	Red	16.22	11.30	65.7	33.31	38.1
	LSD (df = 21)	**n.s.**	**n.s.**	**n.s.**	**3.27**	**n.s.**
Surfactant	With surfactant	16.43	12.43	69.1	36.12	40.2
	Without surfactant	15.75	11.91	66.3	35.20	38.6
	LSD (df = 21)	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
Aeration× Soil type	Aeration×Black	15.89	12.84	70.1	38.62	41.3
	Aeration×Red	15.57	11.08	64.4	32.85	37.7
	Control×Black	16.03	13.22	69.4	37.42	40.2
	Control×Red	16.87	11.53	67.0	33.77	38.5
	LSD (df = 21)	**n.s.**	**2.03**	**n.s.**	**4.62**	**n.s.**
Aeration× Surfactant	Aeration×with Surfactant	15.22	11.53	65.5	34.85	38.8
	Aeration×without Surfactant	16.23	12.39	68.9	36.62	40.3
	Control×with Surfactant	17.64	13.32	72.7	37.40	41.7
	Control×without Surfactant	15.27	11.43	63.7	33.78	37.0
	LSD (df = 21)	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
Soil type× Surfactant	Black×with Surfactant	15.83	12.56	68.5	37.33	40.1
	Black×without Surfactant	16.08	13.49	70.9	38.71	41.4
	Red×with Surfactant	17.03	12.29	69.7	34.92	40.4
	Red×without Surfactant	15.42	10.32	61.6	31.70	35.9
	LSD (df = 21)	**n.s.**	**2.03**	**9.2**	**n.s.**	**5.1**
Aeration×Surfactant×Soil type	Aeration×with Surfactant×Black	15.76	12.13	66.9	36.42	39.0
	Aeration×without Surfactant×Black	16.01	13.55	73.2	40.83	43.6
	Aeration×with Surfactant×Red	14.69	10.93	64.1	33.28	38.5
	Aeration×without Surfactant×Red	16.45	11.23	64.6	32.41	36.9
	Control×with Surfactant×Black	15.91	13.00	70.1	38.25	41.2
	Control×without Surfactant×Black	16.15	13.44	68.7	36.58	39.1
	Control×with Surfactant×Red	19.36	13.65	75.2	36.55	42.2
	Control×without Surfactant×Red	14.38	9.42	58.7	30.98	34.9
	LSD (df = 21)	**n.s.**	**2.87**	**13.0**	**6.54**	**7.2**

*: P<0.10

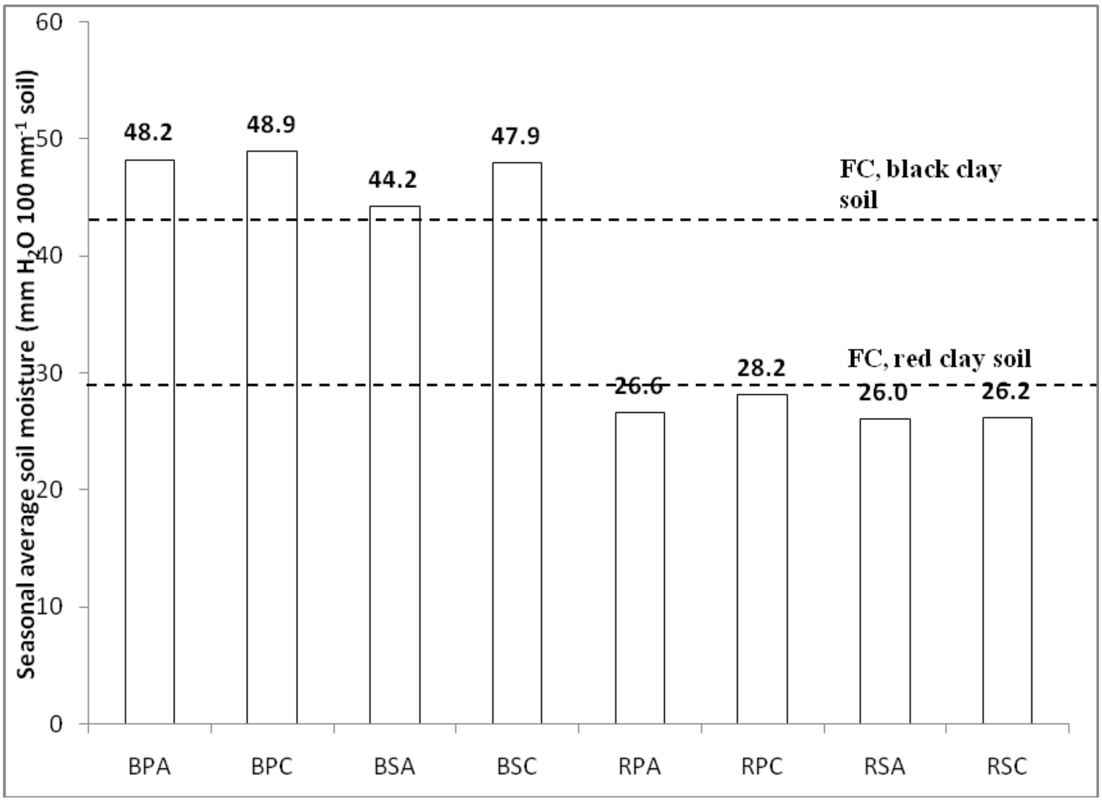

Figure 8. 6 Seasonal average soil moisture (after cessation of irrigation) for the treatments in Chapter 8. Abbreviations as in Figure 8.1.

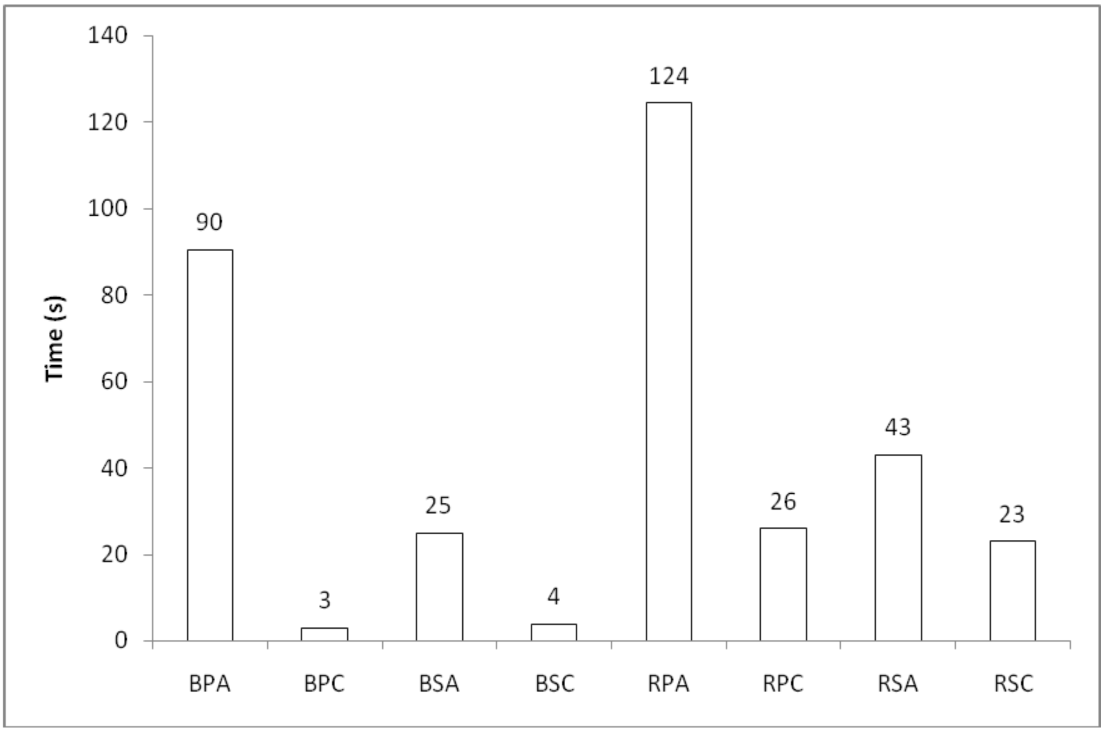

Figure 8. 7 Estimated time for consumption of the calculated oxygen by vegetable soybean roots. Abbreviations as in Figure 8.1.

the first block of the aerated treatments and the same parameters from the corresponding entire control treatments are presented in Figures 8.8-8.11. Aeration of Vertisol with water alone increased the number of nodes, the total as well as marketable number of pods, and the weight of total pods (Figure 8.8). Nonetheless, the weight of leaves, stems and aboveground biomass for the first block of BPA was less than the corresponding parameters for the entire block of BPC. The number of leaves per plant, canopy light interception, and the weight of marketable pods were almost unaffected. In contrast to BPA, aeration of Ferrosol with water alone consistently increased all the aforementioned parameters in comparison to the corresponding non-aerated treatment (Figure 8.9).

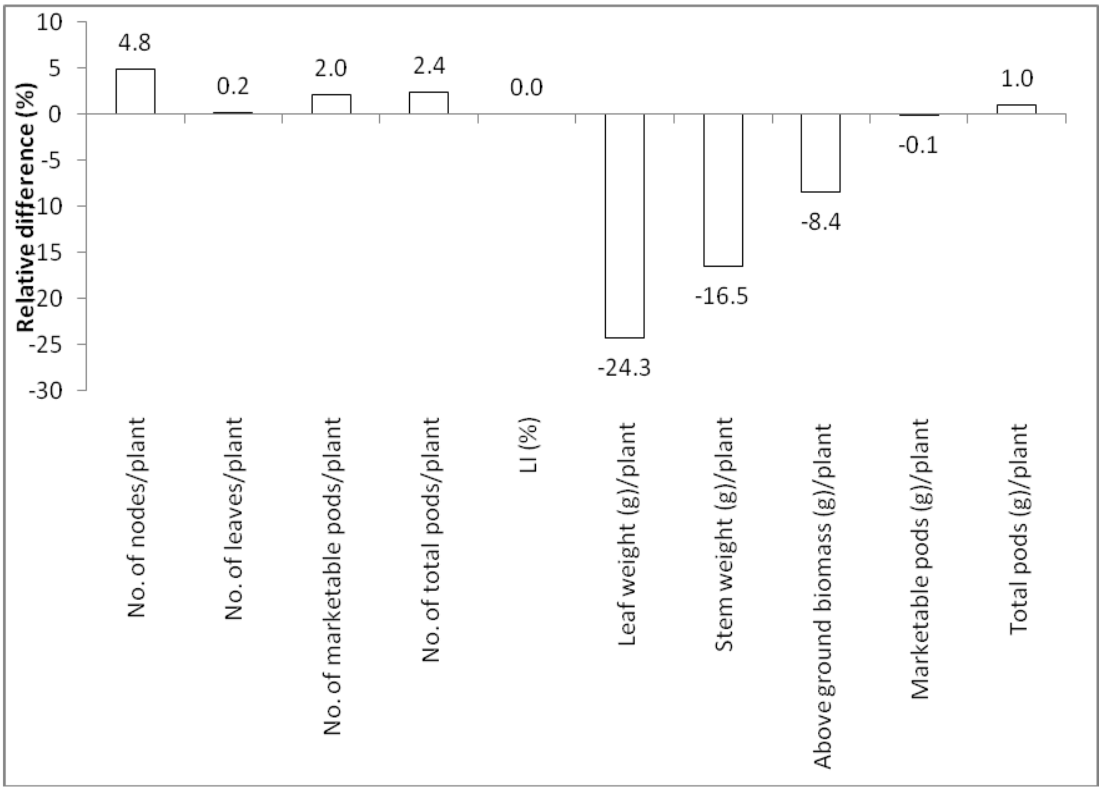

Figure 8. 8 The relative differences in the growth parameters and yield components of vegetable soybean between the first block of Vertisol, no surfactant, aerated treatment (BPA) and the entire blocks of the respective control (Vertisol, no surfactant, not aerated treatment, BPC).

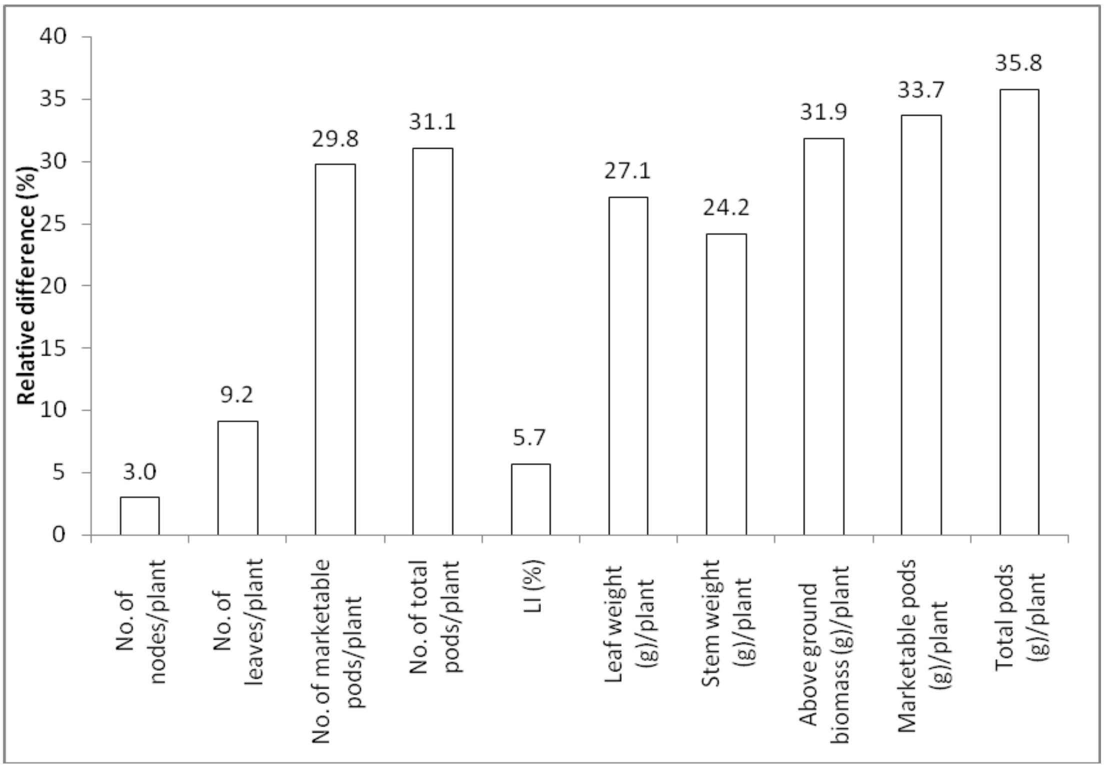

Figure 8. 9 The relative differences in the growth parameters and yield components of vegetable soybean between the first block of Ferrosol, no surfactant, aerated treatment (RPA) and the entire blocks of the respective control (Ferrosol, no surfactant, not aerated treatment, RPC).

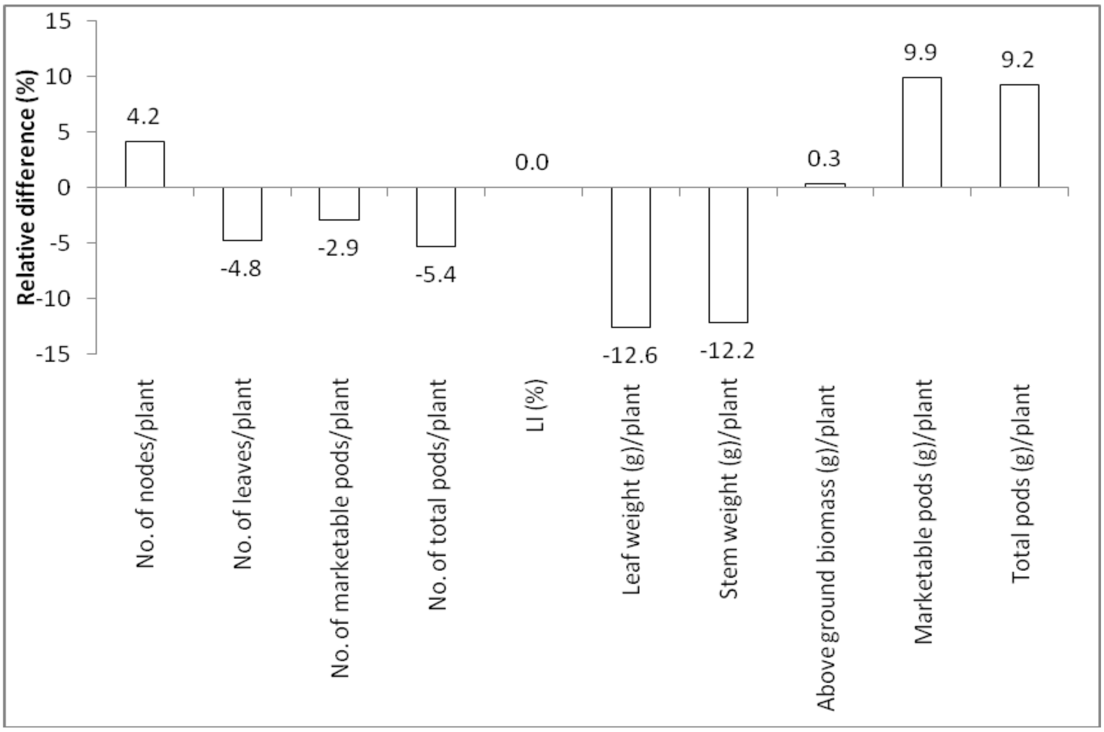

Figure 8. 10 The relative differences in the growth parameters and yield components of vegetable soybean between the first block of Vertisol, with surfactant, aerated (BSA) and the entire blocks of the respective control (Vertisol, with surfactant, not aerated treatment, BSC).

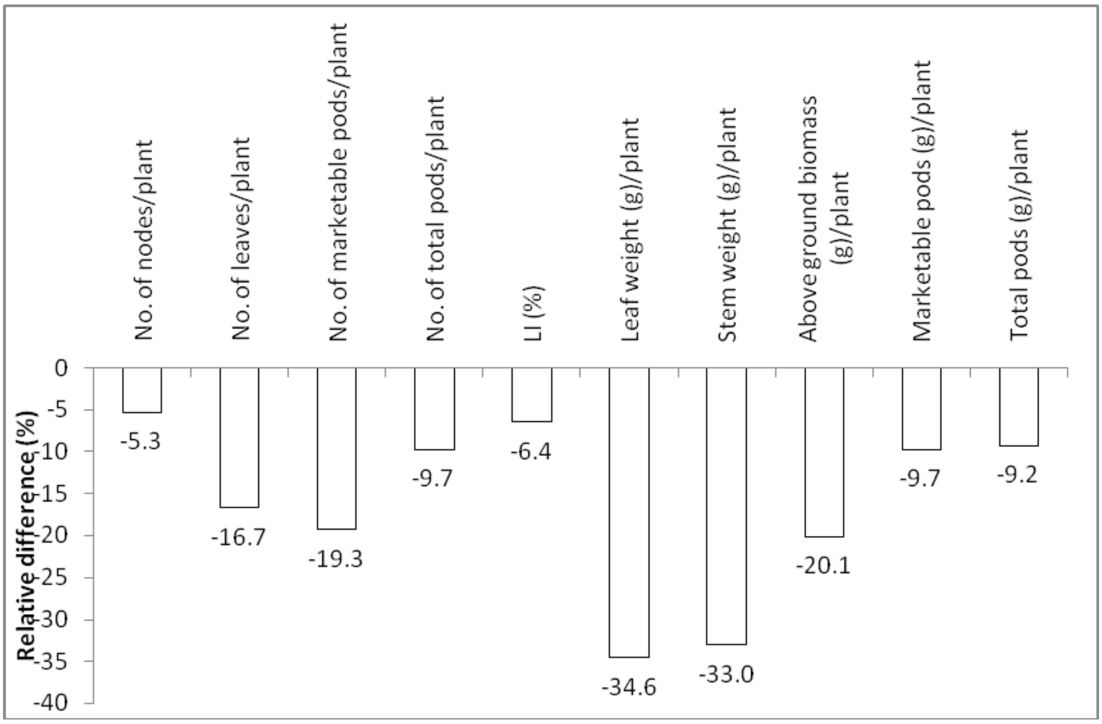

Figure 8. 11 The relative differences in the growth parameters and yield components of vegetable soybean between the first block of Ferrosol, with surfactant, aerated treatment (RSA) and the entire blocks of respective control (Ferrosol, with surfactant, not aerated treatment, RSC).

Utilisation of surfactant in the irrigation water increased the number of nodes in the first block of BSA, and the weight of above ground biomass, marketable and total pods in comparison to BSC (Figure 8.10). However, a reduction in the weight of leaves, stems, and the number of leaves and marketable and total pods was observed for the first block of BSA when compared to BSC. In contrast to the treatments with Vertisol irrigated with surfactant, the first block of the aerated Ferrosol irrigated with surfactant consistently showed a reduction in the number or weight of the growth parameters and the yield components in comparison to RSC (Figure 8.11).

8.4 Discussion

During the growing season, all treatments were irrigated daily for seven hours and the pots were provided with identical drainage facilities in terms of the diameter and the number of holes at their base for drainage of excess water. However, in contrast to the treatments with Ferrosol in which the average soil moistures were moderately below the FC, the treatments with Vertisol generally showed soil moistures above the FC. This is mainly attributed to the difference in the permeability of these two soil types. Black Vertisol contains 35% or more by weight of clay particles, and is classified as a swelling soil with a very low to moderate hydraulic conductivity in the range of 0.1-10 mm h^{-1} (Shaw & Yule 1978; Forrest et al. 1985; Bird, Willis & Melville 1996; McKenzi et al. 2004), and is also generally rich in nutrient elements (Irvine & Reid 2001). There were no data for soil particle size analysis, nutrient elements, or permeability measurements for either Vertisol or Ferrosol samples used in this experiment. However, it is likely that the high clay content and particularly the swelling property of the soil resulted in poor drainage and consequently high water contents after irrigation events in the treatments with Vertisol (Figure 8.6). In contrast to the Vertisol, the Ferrosol is defined as a non-swelling clay and strongly formed aggregates resulting in reportedly extremely high permeability around 1000 mm h^{-1} (Bridge et al. 1996; McKenzie et al. 2004). The high permeability of Ferrosol allowed for fast drainage of the excess water during and after the prolonged daily irrigation events, so that after cessation of irrigation, the macropores were effectively drained and consequently led to relatively lower soil moistures (Figure 8.6).

Surfactant apparently lowered slightly the soil moisture in both soil types. Application of surfactant to soil at concentrations below the critical micelle concentration (the concentration at which micelles begin to form; considered to be 1-

5 mg L^{-1} for BS1000™) leads to reduction in the water holding capacity of the soil, and therefore to increased drainage water loss (Rosen 1989). The reduction is as a result of decrease in both the water surface tension and the contact angle between the soil and water. Some difference in seasonal average soil moisture was observed between treatments with or without surfactant in both soil types; those with surfactant having slightly less water content.

The higher soil oxygen concentration in the aerated treatments in comparison to those in the control during and after irrigation events suggests that the roots of the aerated plants may have functioned relatively better than the non-aerated plants. Moreover, the smaller relative difference in the soil oxygen concentration between RSA and RSC (15%, from Figure 8.4) in contrast to the bigger relative difference in the soil oxygen concentration between BSA and BSC (23%, from Figure 8.5) could be attributed to the relatively better drainage condition of the Ferrosol compared to that of the Vertisol. Also, it should be noted that all the soil oxygen measurements were made in the first block of the treatments, where the largest average emitter air flow rates were measured for the aerated treatments.

A marked drop was observed in the emitter water flow rates in the first block of the treatments which were aerated with water only. The reduction in the water flow rate of the emitters which were proximal to the venturi air injector is attributed to the displacement of water by the relatively high air flow rate in this location of the lateral pipe. Similar reductions in the water flow rate of the emitters proximal to the venturi have been observed in Chapters 3 and 6.

Data for the measured average air flow rates from the emitters indicate that a direct relationship exists between the mean air flow rate and the efficiency of air bubble delivery, but an inverse relationship holds between CUC and the mean air flow rate in the open-end oxygation system (where excess air or water was directed toward a drain) used in this experiment. The same relationships were observed between the mean emitter air flow rate and the efficiency of air bubble delivery, and between CUC and the mean air flow rate in the recirculating drip irrigation system (where excess air and water flow back to the irrigation tank) for the vegetable experiments in Chapter 6. The non-uniformity in the distribution of average emitter air flow rates across the aerated blocks without surfactant (i.e. RPA and BPA) in this experiment were similar to those in Chapter 6 except that the magnitude of the average emitter air flow rates for the second, third, and fourth blocks in Chapter 6 were a little larger than the corresponding values for RPA and BPA. This difference is attributed to the greater pressure differential maintained across the venturi for the vegetable experiment (186 kPa) compared to the pressure differential across the venturi for RPA or BPA (131 kPa).

The data clearly show that addition of surfactant reduced the magnitude of the air flow rates from the emitters and only slightly enhanced (but not significant at $P<0.10$) the distribution of air bubbles along the lateral pipes. This is explained as follows. For a given pressure differential across a venturi, a certain volume of air in the form of air bubbles with relatively large diameters are introduced into the pipe in a given time interval. In a drip irrigation system with asymmetric connectors, the majority of the air bubbles will be discharged by the first few emitters located close to the venturi and consequently little air bubbles will be left for the distal emitters, thereby resulting in a non-uniform emitter air flow rate distribution. When surfactant of a given concentration is added to water, due to the reduction in water surface tension, the diameter of the air bubbles will be reduced but their number will be increased accordingly (Rosenblit et al. 2006). These changes in the diameter and number of air bubbles will have two consequences. First, the average emitter air flow rate will be decreased because air bubbles of relatively small diameters are now available to the emitters. Second, in contrast to the case where pure water was used, more air bubbles (of small diameter) will be available for the distal emitters leading to an enhanced uniformity in the emitter air flow rate. However, it should be taken into account that in an open-end irrigation system part of the total air supplied by the venturi will leave the system as unused air bubbles, thereby reducing the efficiency of air bubble delivery as well as the average emitter air flow rate. All these outcomes are in agreement with the results and supported by data reported in section 3.3.2 (Figures 3.23 and 3.24) of Chapter 3. It should be noted from Figures 3.23 and 3.24, application of surfactant at a concentration of C_f = 1.2 ppm resulted in average emitter air flow rate, efficiency of air bubble delivery, and CUC of 1.3 L h^{-1}, 33%, and 80%, respectively. These outcomes are comparable with the corresponding values presented in Table 8.2. The relatively smaller average emitter air flow rate for BSA or RSA (0.55 L h^{-1}) compared to that presented in Figure 3.22 (1.3 L h^{-1}), is possibly due to the higher surfactant concentration in this experiment (C_f = 2 ppm). It was interesting that the decreasing effect of surfactant on the average emitter air flow rate and its enhancing effect on the CUC in this experiment were observed in all the trials with dead-end drip irrigation systems used in Chapter 3. An important conclusion from these observations is that the relationships between mean emitter air flow rate and efficiency of air bubble delivery, and between mean emitter air flow rate and CUC are independent of the drip irrigation system (i.e. the relationships are true for recirculating systems, as well as for open-end systems and dead-end systems).

Data presented in Figures 8.8-8.11 clearly indicate a conspicuous difference in the response of soil type to oxygation, with or without surfactant. As both RPA and BPA received almost the same emitter air flow rates (Table 8.2), the consistently enhanced growth of the plants in RPA (Figure 8.9) in contrast to that in BPA is attributed to the higher permeability of the Ferrosol in comparison to the Vertisol. It should be noted that although the hydraulic conductivity of the soils were not measured, the average seasonal soil moisture could be considered as an indicator of the permeability condition of the soils. Both soil types were aerated during irrigation events, however, the relatively faster drainage of excess water in the Ferrosol provided better conditions for the roots for respiration and possibly uptake of nutrients in contrast to the Vertisol. This is further supported by the greater canopy light interception (LI) in RPA in comparison with that in BPA. There was no difference between the LI for the first block of BPA (where the largest emitter air flow rates were delivered and hence the strongest effect of oxygation was expected) and that of the entire blocks of BPC. In contrast to BPA, the measured LI for the first block of RPA was ~ 6% larger than that for the entire blocks of RPC, suggesting a relatively enhanced root aeration and possibly more water and nutrient uptake resulting in a larger LI. Bhattarai, Midmore & Pendergast (2008) reported that oxygation of soybean in a Vertisol resulted in 43% increase in the fresh weight of the pod. Although in my experiment, aeration generally increased the crop yield compared to the control, the difference was not as large as that obtained by Bhattarai, Midmore & Pendergast (2008). Since details about pipe diameter, connector type, piping layout, and distribution of (measured) emitter air flow rates were not provided by Bhattarai, Midmore & Pendergast (2008), it is not possible to identify the reason(s) for the great difference in the response of the oxygated treatments in the two experiments.

Application of surfactant with the oxygation of Vertisol did not cause consistent outcomes to growth parameters and yield components. Although addition of surfactant to the aerated irrigation water clearly improved the uniformity of air flow rates along the irrigation pipe, the level of air flow rates in the first block of BSA was not sufficiently high to overcome the impacts of high soil water content in the root zone. Application of surfactant in the aerated water caused poorer plant performance in the first block of RSA in comparison with the plants in the first block of BSA. These outcomes are attributed to the low level of emitter air flow rates in the aerated treatments and the relatively poorer nutrient status of the Ferrosols in comparison to the Vertisols. The short estimated time for consumption of the calculated oxygen in the root zone of both BSA and RSA (Figure 8.7) explains the poor effect of oxygation in the aerated treatments with surfactant. Also, it is likely that the relatively better performance of plants in the first block of BSA in comparison with that of the first block of RSA was due to the difference in the cation exchange capacity (CEC) of these two soil types. The dominant clay type in black Vertisols is smectite with a high CEC in the range of 80-150 meq 100 g^{-1} (Velde 1995). The CEC is defined as the degree to which a soil can adsorb and exchange cations. In contrast to the black Vertisols, the major clay type in the red Ferrosols is kaolinite and gibbsite with relatively low CEC ranging from 3-15 meq 100 g^{-1} (Donn, Menzies & Rasiah 2004; Irvine & Reid 2001; McKenzie et al. 2004; Velde 1995). Since the nutrient requirement of the treatments was supplied through daily fertigation (supplying fertilizer through subsurface drip irrigation), the smaller CEC for the Ferrosol might explain the inferior performance of the aerated block in Figure 8.11 in comparison with Figure 8.10.

An overview of the results presented in Tables 8.3 and 8.4 reveals that soybean showed a weak response to the root zone aeration whereas soil type was the major factor that caused significant differences. According to the findings reported by Boru et al. (2003) soybean tolerates anaerobiosis and soil saturation very well, but will be damaged under hypoxic conditions where concentration of carbon dioxide in the rhizosphere increases to 30% by volume. Moreover, Griffin and Saxton (1988) investigated the effect of flood duration at the V6 (vegetative), R2 (bloom), or R2 + R5 (bloom and pod fill) growth stages. Within each timing treatment, water was applied to a standing depth of 76 mm and allowed to stand for 0 (non-flooded, control), 1, 2, 4, or 8 days. Soybean stand density did not change as flood duration increased. Yields for individual timing treatments were generally similar when flood periods were 0, 1, or 2 days. When water was held longer than two days post-flowering, significant yield reductions were noted. In my oxygation experiment, although the seasonal average soil moisture (Figure 8.2) over the soil profile for the Vertisol was always above the FC, the drainage facility at the bottom of the containers kept the soil moisture below the FC down to 10 cm from the soil surface over the crop season (data not shown). Also, the CO_2 produced as a result of root and microbial respiration was possibly dissolved in the water and eventually drained from the bottom of the containers. Hence, it is likely that the tolerance of soybean to waterlogging and the drainage of excess water from the root zone were responsible for the non-significant difference in the plant performance between the aerated and control treatments in this experiment.

8.5 Conclusions

Among the main factors tested in this experiment, soil type had a prominent effect on the canopy light interception, number of nodes per plant, and marketable pods. The differences were attributed to either the differences between the soils in permeability and/or cation exchange capacity.

Application of surfactant on average consistently (but not significantly) increased the crop yield and yield components in all the treatments. Moreover, it seems that addition of surfactant to the soil at a concentration below its critical micelle concentration would result in enhanced soil permeability through reduction of the water holding capacity of the soil.

Although addition of surfactant to the aerated water led to a relatively enhanced uniformity of the air flow rates along the irrigation pipe, the magnitude of air flow rates even within the first block of the treatments (for either soil type) was too low to make a significant improvement in the plant performance. The relatively high emitter air flow rates in the first block of the aerated Ferrosol or Vertisols without surfactant resulted in accordingly lower water flow rates but relatively enhanced number of nodes, marketable pods, and total pods per plant compared to the controls. These outcomes suggest that further enhancement in the plant performance is attainable if emitter air flow rates equal to or greater than those measured for the first block of BPA or RPA (~ 8 L h^{-1}) could be supplied to the plants in the distal blocks.

The results of this experiment revealed that the non-uniformity in the distribution of emitter air flow rates is a major shortcoming of oxygation when a single lateral pipe is used for conveyance of air flow from the venturi. Application of surfactant in the open-end irrigation system of this experiment resulted in a high CUC, but air flow rates were too low for any reasonable effect on plant performance. One possible solution for further improvement in crop yield is to use microdrip emitters (<0.5 L h^{-1}) instead of conventional emitters (>2 L h^{-1}). Use of low flow rate emitters markedly increases oxygation time without notable reduction in the emitter air flow rate (for more details see Section 3.4.1.1, Chapter 3).

Chapter 9: General conclusions and future research

Transitory flooding or extended irrigation accompanied by poor drainage may impede root respiration by limiting the availability of soil oxygen. Waterlogging and insufficient soil aeration results in anaerobic conditions. In flooded or waterlogged soils, oxygen shortage is considered as one of the main root stresses. Oxygen deficiency in the rhizosphere can adversely affect some physiological processes such as shoot and root hormone relations, uptake and transport of ions through roots leading to nutrient deficiencies, and water absorption.

Aeration of subsurface drip irrigation (SDI) has been shown to alleviate soil hypoxia/anoxia by providing air/oxygen to an oxygen-depleted plant root zone. This can be achieved by coupling an air injector venturi to draw air into the subsurface drip irrigation system. However, there is evidence indicating a declining trend in the plant performance along lateral lines beginning 50 m from the venturi which could be associated with decreasing air flow along the length of laterals away from the location of the venturi. Oxygation of pot grown grain sorghum with two levels of aerated water using a recirculating irrigation system and symmetric connectors showed no significant difference in the growth parameters between the aeration treatments and the control. The very low efficiency of air bubble delivery associated with symmetric connectors in recirculating irrigation systems, preferential flow in branching pipe systems with an odd number of laterals (three laterals in this experiment), and the elevated water temperature which increased oxygen requirement for root and microbial activities and lowered the oxygen solubility in water were responsible for the non-significant effect of oxygation on the aerated treatments. Clearly, the use of symmetric connectors for recirculating irrigation systems is not recommended as they yield very low efficiency of air bubble delivery compared to the asymmetric connectors.

In a pot experiment with a branching pipe system and emitters placed at 5 and 20 cm from the soil surface, capsicum plants irrigated with the shallow emitters performed significantly better than those irrigated with deep emitters. The branching pipe system caused a failure of the delivery of air to the aeration treatments. The enhanced performance of the shallow emitter treatments over the deep ones was attributed to the higher relative gas diffusivity prevailing in the shallow treatments. It was clearly shown that in a recirculating drip irrigation system with certain branching pipe set-ups, preferential flow of air bubbles will lead to a failure of root zone aeration.

The behaviour of air and water flow in branching pipe systems is quite complex and it is difficult to predict how the two phases are distributed among the pipes. Some studies have been done on the two-phase flow (air and water) in branching pipe systems (with no outlets, i.e. no emitters on the pipes) for analysis of the conditions where preferential flow of air takes place. It was found that in a two-phase flow with a branching pipe system, distribution of the phases among the pipes depends upon the junction geometry, pipe slope, length and diameter of the pipe, inlet flow rates and their physical properties. Nonetheless, there are no reports addressing the issue of preferential flow of air or the uniformity of air flow distribution along a lateral pipe in an oxygated drip irrigation system.

Different layouts of branching lateral pipes were tested for the preferential flow of air bubbles in drip irrigation systems. It was hypothesised that the air bubbles flowed into the first relative low pressure zone(s) encountered. The relative low pressure zone(s) was (or were) always located closest to the junction point of the main pipe and the manifold for all the configurations tested in the trials. Further research considering the factors influencing preferential flow of air and water flow into the group of lateral pipes of a drip irrigation system such as pipe characteristics (e.g. slope, length and diameter), fluid characteristics such as the ratio of inlet air flow rate to the water flow rate, and their physical properties (pressure and velocity) is suggested. Furthermore, it is suggested to use small size venturis at the beginning of every lateral line instead of using a big venturi for a group of lateral pipes, to avoid the risk of preferential flow of air bubbles in branching pipe systems. This is feasible only if the required motive flow rate and pressure differential can be supplied for the small size venturis.

A large portion of the experimental work of this thesis was designed to analyse the factors that affect the distribution of emitter air flow rates along irrigation pipes and the ways to enhance the distribution uniformity. The factors which were studied consisted of emitter cross sectional area (CSA), pipe diameter, connector geometry, insertion of goof plugs immediately after a connector, and addition of surfactant to the irrigation water. It is noteworthy to mention that part of the uniformity trials were performed using a recirculating irrigation system instead of a dead-end system; the latter is normally used in the field. The reason for this design was that sustaining a given pressure differential across a given venturi will lead to introduction of a given air flow rate into the pipe only if a minimum motive (water) flow rate is maintained across the venturi. For glasshouse applications, where the summation of the water flow rates of all the emitters in a drip irrigation system are usually smaller than the minimum motive flow rate of a conventional venturi, a recirculating system might be a solution. Unfortunately, part of the total air supplied by the venturi might flow back to the irrigation tank and hence lead to a reduction of the efficiency of air bubble delivery of the oxygation system.

Cross sectional area (CSA) is a key characteristic of an emitter; the larger the CSA, the larger will be the flow rate. It was shown a 242% reduction in the emitter water flow rate was associated with only a 59% reduction in the average emitter air flow rate. However, the distribution of the emitter air flow rates (measured by Christiansen's uniformity coefficient) for the small emitters was 10 times better than that for the large emitters. Generally, in all trials concerning emitter air flow rates, a lower average air flow rate was associated with a higher uniformity between emitters. This association is ascribed to the effect of any change in the hydraulic conditions of the flow (such as addition of surfactant, use of goof plugs, increased protruded length of connector relative to the diameter of the pipe), that reduces the availability of air bubbles to the proximal emitters and subsequently availability of more air bubbles to the distal emitters, thereby improving the uniformity of emitter air flow distribution. Further research on emitters with a wide range of CSAs should be done in order to establish a relationship (a correlation) between emitter CSA and average air flow rate for a given supply of air flow from the venturi.

In addition to the emitter CSA, pipe diameter and connector geometry have a prominent influence on the average emitter air flow rate and its distribution along a pipe. In drip irrigation systems with symmetric connectors, the availability of air bubbles to emitters is a function of the submerged length of connectors (SLC) in the region occupied by the air bubbles flowing at the top of the irrigation pipe. In other words, SLC is the difference between the depth of the region occupied by the air bubbles and the length of the connector. The larger the SLC, the larger will be the emitter air flow rate. As a given volume of air enters into an irrigation pipe, it occupies a certain depth at the top of the pipe the magnitude being dependent upon the diameter of the pipe. The larger the pipe diameter, the smaller will be the depth of the region occupied by the air bubbles and hence the SLC will become shorter. This explains the direct relationship between average emitter air flow rate and pipe diameter when symmetric connectors were used. In design of an oxygation system, it is very important to take into consideration that a decrease in the pipe diameter will not only lead to an increase in the SLC, but will also result in an increase in friction loss and hence an increase in the pumping cost and energy consumption.

In contrast to symmetric connectors, the local turbulence at the tip of asymmetric connectors, together with the submerged length of connectors, contributes to the availability of air bubbles to emitters. Formation of the local turbulent flow is mainly due to the effect of drag force exerted by the moving water on the asymmetric portion of the protruded length of the connector. Generally, drag is an opposing force which acts on an object when it moves through the fluid, or the fluid moves against it. The magnitude of the drag force depends on the fluid density, the frontal area of the object, the dimensionless geometry-dependant drag coefficient, and most importantly, the velocity of movement. Drag force is proportional to the second power of water velocity. The direct relationship between the average emitter air flow rate and pipe diameter with asymmetric connectors is due to the higher velocity in the pipes with larger diameter, which in turn causes greater drag force.

For a given pipe diameter, the average emitter air flow rate from asymmetric connectors was larger than that from symmetric connectors. The reason is that for asymmetric connectors, two factors are involved in the delivery of air bubbles to emitters (i.e. the local turbulence at the vicinity of the tip of the connector, and the submerged length of the connector), whereas for symmetric connectors only one factor (the submerged length of connector) controls the availability of air bubbles to the emitters.

The addition of surfactant to water lowers the water surface tension. For a given volume of air bubbles in an irrigation pipe, reduction in the water surface tension leads to reduction in the diameter of air bubbles and accordingly increases the number of air bubbles. Hence, one solution to improve the uniformity of emitter air flow rate distribution along irrigation pipes is the addition of surfactant to the irrigation water. The results obtained from application of different concentrations of a nonionic surfactant in a recirculating irrigation system indicated an inverse relationship between surfactant concentration in the irrigation water and average emitter air flow rate, the maximum emitter air flow rate, and the efficiency of air bubble delivery. There was a direct relationship between the concentration of surfactant in irrigation water and the uniformity of the distribution of emitter air flow rates along the irrigation pipe. Likewise, addition of surfactant to the irrigation water in dead-end drip systems generally led to a reduction of the average emitter air flow rates. It was hypothesized that in some sampling locations, all or part of the volume of water displaced by the air bubbles was not measurable by the measuring cylinder, the accuracy of which was ±10 mL. Moreover, the volume of the suspending micro air bubbles in the sampled water was ignored. Additionally, it is possible that the depth of the region occupied by air bubbles (at the top of the pipe) in the downstream end of the lateral might have been too short to be influenced by the local turbulence created at the tip of the asymmetric connector. Hence, the average emitter air flow rate in the presence of surfactant was relatively smaller than that in the absence of surfactant. The same positive effect on the CUC, although weaker in comparison with that of surfactant, was consistently observed as a result of application of goof plugs in the irrigation systems. Regardless of the geometry of connectors, addition of surfactant together with insertion of asymmetric goof plugs immediately before the connectors, resulted in the highest recorded air flow rate uniformities (about 50%). It is recommended to test different formulations of non-ionic surfactants or combinations of two or more than two surfactants to obtain maximum enhancement in uniformity of air flow rate distribution. Non-ionic surfactants are preferred over anionic or cationic surfactants as they are not likely to interfere with nutrient ions. Some important factors that should be taken into account when choosing a surfactant are: low critical micelle concentration, high solubility in water, low toxicity for plants, animals and humans. Ability to be recycled, and its cost, public and regulatory perception, and biodegradability also need to be considered. Moreover, application of surfactant to irrigated soils reportedly leads to an increase in the soil infiltration rate through a reduction in the interfacial tension of soil and water. Therefore, it is suggested to study the long-term impacts of surfactants on soil physical properties (hydraulic conductivity, bulk density, and so on), even though a biodegradable one is used.

Replacing a branching pipe system with a single pipe with returns in alternate rows of pots (viable for small size drip irrigation systems in glasshouses) will prevent the risk of preferential flow of air bubbles. It should be mentioned that replacing a branching pipe system with a single pipe system may involve higher costs and hence may not be sustainable for field drip irrigation systems. In a number of trials where a single lateral pipe was used, a declining trend in the distribution of emitter air flow rates along the irrigation pipes was evident and limited the positive effect of oxygation on crop yield. Moreover, very often a relatively high air flow rate (i.e. ~ 8 L h^{-1}) from the proximal emitters with asymmetric connectors caused a drop off (up to 42 %) in the water flow rate of those emitters. Depression of water flow rates from the proximal emitters as a result of very high rates of emitter air flow, adversely affects the water distribution uniformity. Poor water distribution uniformity may lead to non-uniform plant growth and/or water stress.

Addition of surfactant to the irrigation water in an open-end irrigation system with asymmetric connectors and single lateral pipes for pot vegetable soybean led to smaller average emitter air flow rates (and consequently no reduction in the emitter water flow rate), and better CUC for the emitter air flow rates compared to the aerated treatments without surfactant. Nevertheless, the efficiency of air bubble delivery and the average emitter air flow rate for the aerated treatments with surfactant were remarkably smaller than those for the aerated treatments without surfactant. Despite the enhanced uniformity of the emitter air flow rates in the aerated treatments with surfactant in comparison with those in the aerated treatment without surfactant, plant performance was relatively better in the aerated treatments without surfactant. The reason is ascribed to the higher average emitter air flow rate delivered by to the treatment without surfactant compared to that for the treatment with surfactant. Possibly, use of very low flow rate emitters (<0.5 L h^{-1}) instead of the conventional emitters (>2 L h^{-1}) together with surfactant in irrigation water in open-end irrigation systems might be a solution to this issue. Although addition of surfactant decreases the average emitter air flow rate, use of very low flow rate emitters (also known as microdrip emitters) increases the oxygation time and thereby plant performance is expected to be improved. Since the water passage dimensions in microdrip emitters are much smaller than in the conventional ones, microdrip emitters are more susceptible to clogging and hence poor water distribution uniformity. Emitter clogging is a major issue in micro irrigation systems and may result from solid particles, organic materials (algae and/or bacterial slime), or chemical precipitates. Regular flushing of lateral lines together with chemical treatment and adequate filtration are means generally applied to control emitter clogging.

The response of four vegetable species of different rooting morphology comprising of pak choi and spring onion (fibrous root), and dwarf bean (taproot) and beetroot (modified taproot) to root zone aeration was studied. The declining distribution of air bubbles across the aerated experimental blocks led to insufficient supply of oxygen to the root zone of the species and hence a non-significant difference between all the aerated and control treatments, except for spring onion. Possibly, the relatively higher sensitivity of spring onion to oxygen deficiency was responsible for the significant effect of aerated water on the yield and yield components of this species. Crop species employ a variety of mechanisms to cope with and adapt to oxygen deficiency in the root zone. Possibly, the intrinsically high tolerance to hypoxia (in beetroot), or shallow rooting (in pak choi), or aerenchyma formation (in bean) was responsible for the non-significant difference of the plant performance between the aerated and non-aerated treatments.

The effect of root zone aeration by means of the Mazzei air injector and the Seair diffusion system on wheat yield and yield components were investigatedBoth aeration treatments showed non-uniform emitter air flow rate distribution along the lateral pipes with the highest average air flow rates delivered by the emitters proximal to the venturi and the smallest air flow rates delivered by the distal emitters. In this experiment with superficially placed emitters, almost with every irrigation event, air bubbling from the soil surface was observed. Generally, the aerated treatments showed relatively enhanced performance in comparison with the control.

The growth parameters as well as the yield components were the highest for the Mazzei treatment followed by the Seair treatment and the lowest were for the control. Nevertheless, with the exception of the leaf chlorophyll concentration, no growth parameters differed significantly (at 10%) between the control and the aerated treatments. The non-significant differences between the aerated treatments and the control were attributed to the insufficient emitter air flow rates and to air bubbling at the soil surface.

Deeper placement of the emitters (e.g. at 20 cm) will possibly prevent air bubbling from the soil surface and lead to availability of more oxygen to the root zone. When considering improvements in efficiency of the Seair treatments, storage of the super-aerated water from the diffusion chamber into a pressure vessel at least of the same pressure as in the diffusion chamber might prevent loss of air bubbles from the water tank into the air and consequently lead to availability of more air to the plant roots in those treatments.

In summary, the results of the experiments in this research elucidated the effect of emitter cross sectional area, geometry of connector, and pipe diameter on the efficiency of air bubble delivery, the average, and uniformity of emitter air flow rates along lateral pipes. Also, it was shown that insertion of asymmetric goof plugs together with addition of surfactant to irrigation water resulted in the highest uniformity (~ 50%) in the distribution of emitter air flow rates. Moreover, preferential flow of air into branching pipe systems might adversely influence the efficacy of oxygation systems. Oxygation positively enhanced the growth parameters for a number of species including soybean, wheat, pak choi, spring onion, and bean. However, maintaining an average emitter flow rate of ~ 8 L h^{-1} along a lateral pipe will possibly lead to an assured significant increase in crop yield.

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