Response of potato (*Solanum tuberosum*) tuber yield components to gel-polymer soil amendments and irrigation regimes

B. K. Eiasu
P. Soundy
P. S. Hammes

Department of Plant Production and Soil Science, University of Pretoria, Pretoria 0002, South Africa
email: bkef68@yahoo.com

Abstract Two field experiments were conducted to investigate the effects of two gel-polymer formulations (pure and fertiliser-fused) and moisture stress on yield and quality of potato (*Solanum tuberosum*). The experiments were carried out at the Hatfield Experimental Farm of the University of Pretoria, South Africa. Six gel-polymer rates, consisting of pure gel polymer at 1.5 kg/m^3 of soil, with 85% and 70% fertiliser rate of the control, and fertiliser-fused gel polymer at 1.5, 2, and 3 kg/m^3 soil, and control (without gel polymer) were assigned to the subplots. Four maximum allowable moisture depletion (MAD) levels, 25%, 40%, 55%, and 70% of the plant available soil moisture, were allocated to the main plots. Rate of phosphorus (P) was the same for all treatments (168 kg/ha). Total nitrogen (N) and potassium (K) budget for the treatments (except one pure gel-polymer treatment received 85%) were balanced to 70% of the control. The fertiliser-fused gel polymer showed no substantial improvement in tuber yield parameters for all rates. The pure gel polymer, especially at higher fertiliser rate, improved total and marketable tuber yield. Marketable tuber number and yield, and total tuber mass showed declining trend with an increase in MAD. Significant reduction in tuber fresh and dry mass was observed at the 55% and 70% MAD irrigation levels. Both high and low soil moisture levels reduced tuber specific gravity. Incidence of common scab was inversely related to the irrigation frequency.

Keywords common scab; gel polymers; maximum allowable moisture depletion; potato tuber specific gravity

INTRODUCTION

Soil moisture is one of the potato (*Solanum tuberosum* L.) yield limiting factors (van Loon 1981; Yuan et al. 2003). Potato tuber yield shows positive response to soil moisture (Opena & Porter 1999) and to fertilisers, especially to nitrogen (N) and potassium (K) (Spiertz et al. 1996). The sensitivity of the potato crop to irrigation and fertiliser is, at least partially, associated with its production in sandy soils (more preferable for high and quality tuber yield) and the shallow root system of the plant (King & Stark 1997; Peralta & Stokle 2001).

 Scientists are searching for alternative fertilisation and irrigation management practices that maximise crop productivity and minimise environmental hazards. Davenport et al. (2000) reported that a polymer-coated fertiliser reduced the conventional N application of potato production by 50%. Doblende & Lendent (2001)

and Fabeiro et al. (2001) pointed out that deficit irrigation management during vegetative growth did not cause significant reduction in tuber yield. Polyacrylamides and other soil-wetting polymers incorporated into sandy potato fields increased the water retention of the soil around the root zone by 102% while accompanied by an increase of 25% in tuber yield (Watt & Peake 2001).

 Gel-polymer soil amendments enhanced hydraulic properties of sandy soil and reduced evaporation (Choudhary et al. 1995; Al-Darby 1996). According to Hüttermann et al. (1999) and Sivapalan (2001) gel polymers improved soil moisture retention and extended the survival of soybean and Pinus halepensis. Van Rooyen et al. (2002) claimed that the fertiliser-fused gel polymer, Aqua-Soil^{TM} (a combination of nutrients and K-based co-polymers), retains soil moisture and nutrients that would be readily available to plants. A laboratory test carried out at the University of Pretoria proved that the fertiliser-fused gel-polymer formulation minimised nutrient leaching (Anon. 2002). These findings suggest that gel polymers could play a vital role in improving yield and quality of crops such as potato, which suffer from the low moisture and low nutrient retention of sandy soils.

 The study was conducted to: (1) determine the impact of different gel-polymer rates and/or formulations on tuber yield and quality; and (2) identify moisture regimes that minimise irrigation water without significant tuber yield and quality losses.

MATERIALS AND METHODS

Site description

Two field experiments (in autumn and spring) were conducted in 2003, in the Hatfield Experimental Farm of the University of Pretoria, located at 25°45'S and 28°16'E, and an altitude of 1327 m a.s.l. The top 60 cm soil was replaced by homogenous sandy clay loam soil (with a proportion of 72%, 3.3%, and 24.5% coarse sand, silt, and clay, respectively). The autumn field experiment started when air temperature was high (max. 30°C and min. 17°C) and long photoperiod, and both came near their minimum during harvesting (19°C max. and 3°C min.). In the spring, photoperiod was short during planting and long during harvesting; temperature was lower during planting (max. 16°C and min. 6°C) and higher (max. 31°C and min. 16°C) during the harvesting period.

Planting material

In both experiments, a medium maturing potato cultivar (PB1) was used as planting material. To avoid variation between plants as a result of mother tuber size and initial number of stems per plant, seedlings from single-sprouted tuber extracts were raised in trays, and seedlings with uniform growth were transplanted to the field after 2 weeks.

Treatments and experimental design

The experiments were laid out as split plot design, with maximum allowable moisture depletion (MAD) levels assigned to the main plots (9 m in length and 4 m in width) and gel-polymer rates to the subplots (two rows of 3 m long spaced at 0.75 m between

rows for each gel-polymer treatment). Spacing between plants in the same row was 0.3 m. Two gel-polymer formulations were used: pure gel polymer (Stockosorb) and fertiliser-fused gel polymer (Aqua-SoilTM, a formulation consisting of 40% K-linked co-polymer, 30% 3:2:3 (42RS) fertiliser, 15% vermiculite, and 15% gypsum). The following gel-polymer treatments were applied in both field experiments: (1) without gel-polymer amendments (control); (2) fertiliser-fused gel polymer at a rate of 1.5 kg/m^3 soil (Aqua1.5); (3) fertiliser-fused gel polymer at a rate of 2 kg/m^3 soil (Aqua2); (4) fertiliser-fused gel polymer at a rate of 3 kg/m^3 soil (Aqua3); (5) pure gel polymer at a rate of 1.5 kg/m3 soil, with 85% fertiliser rate of the control (ST1.5a); and (6) pure gel polymer at a rate of 1.5 kg/ kg/m^3 soil, with 70% fertiliser rate of the control (ST1.5b).

The gel polymers were incorporated to the soil during land preparation, by thoroughly mixing with the soil to a 0.25 m depth and 0.3 m width in the subplot rows where the seedlings were later transplanted.

The following MAD levels were used as irrigation treatments: (1) plots replenished at 25% maximum depletion level (25% MAD); (2) plots replenished at 40% maximum depletion level (40% MAD); (3) plots replenished at 55% maximum depletion level (55% MAD); and (4) plots replenished at 70% maximum depletion level (70% MAD).

Irrigation scheduling

Irrigation treatment started 3 weeks after transplanting. The control (subplots without gel-polymer amendment) treatment, in each irrigation schedule, was used as the point of reference in irrigation monitoring. Neutron probe readings were taken every alternate day. Treatments were replenished when the neutron probe reading within the 60 cm soil depth of their respective control reached the MAD level. The neutron probe readings were done at 20 cm soil depth intervals. Equation 1 was used in calculating soil moisture depletion percentage (Kashyap et al. 2003).

$$\text{Depletion}(\%) =_{100} \frac{1}{n} \sum_{1}^{n} \frac{\text{FC}_i - \theta_i}{\text{FC}_i - \text{WP}_i} \qquad (1)$$

Where n is the number of layers ($n = 3$ in this instance, where: layer 1, 0–20 cm; layer 2, 20–40 cm; and layer 3, 40–60 cm soil depth), FC_i is the volumetric soil moisture content at field capacity in the ith layer, .i is the volumetric soil moisture content (according to the neutron probe reading), and WP_i is permanent wilting point for the ith layer.

Since the soil in the depth under investigation was transported homogenous soil, moisture retention (volume of water/volume of soil including the pore spaces) at field capacity and at permanent wilting was the same for the three layers, 27% and 16% respectively. The amount of water required to replenish the deficit of each plot to field capacity was estimated by Equation 2 (Kashyap et al. 2003). Accordingly, the time needed for the computer controlled-water pump was programmed based on the number of drippers in each plot and the discharging rate of the dripper.

$$\text{Irrigation water}(m^3) = \frac{\text{MAD}(\text{FC}-\text{WP})R_Z A}{100} \qquad (2)$$

Where R_Z is effective root zone (60 cm), and A is the surface area of each plot (36 m^2). MAD, FC, and WP are in fractions. The average total amounts of water applied to each treatment, from transplanting up to harvesting, are presented in Table 1.

Table 1 Total amount of water (mm) received by each treatment in the two seasons.

Season	Maximum allowable soil moisture depletion level treatments			
	25%	40%	55%	70%
Autumn	356	338	285	214
Spring	401	376	334	276

Fertiliser application

All treatments received 168 kg/ha phosphorus (P) pre-planting. N and K were applied to the treatments in a split form. The control received 122 kg/ha N and 224 kg/ha K pre-planting, and 158 kg/ha N and 76 kg/ha K on the sixth week after transplanting. The ST1.5a and ST1.5b treatments received 85% and 70% of the N and K applied to the control, respectively. Since it had its own fertiliser, neither N nor K was applied to the Aqua-Soil[TM] treatments during planting, but on the sixth week after transplanting, the total N and K rates were balanced to 70% of the total budgets of the control (conventional fertiliser rate for potatoes in the region).

Data recorded

In both experiments, tubers were lifted with a digging fork. After cleaning and sorting the tubers, number and fresh mass of total and marketable tubers, tuber specific gravity, and common scab infestation were recorded. From oven-dried subsamples (at 68°C for 72 h) total tuber dry mass for each observation was calculated. Data were subjected to analysis of variance (ANOVA) using the MSTAT-C statistical software (MSTAT-C 1991).

RESULTS

An increase in gel-polymer rate consistently increased soil moisture retention and decreased soil bulk density (data not presented). Tuber yield performance of potatoes subjected to gel-polymer soil amendments is summarised in Table 2. The total tuber yield performance in autumn was 35%–42% lower than in spring.

Table 2 Impact of gel-polymer treatments on tuber yield in the autumn and spring field experiments. Values followed with the same letter in their respective columns are not significantly different from each other at a = 0.05; control, soil without polymer; Aqua1.5, Aqua2, and Aqua3, fertiliser-fused gel polymer (1.5, 2, and 3 kg/m^3 soil, respectively); ST1.5a and ST1.5b, pure gel polymer (1.5 kg/m^3 soil with 85% and 70% respective fertiliser rates).

Gel polymer treatments	Autumn field experiment		Spring field experiment	
	Total tuber (t/ha)	Marketable tuber (t/ha)	Total tuber (t/ha)	Marketable tuber (t/ha)
ST1.5a	35.06 a	32.43 a	49.96 a	47.51 a
ST1.5b	30.11 b	28.60 ab	47.24 a	44.25 a
Aqua3	26.27 bc	24.76 bc	41.21 b	39.04 b
Control	24.06 c	22.84 cd	40.55 b	37.70 b
Aqua2	21.49 c	19.82 cd	34.12 c	31.99 c
Aqua1.5	21.32 c	19.13 d	28.69 d	25.96 d
Grand mean	26.39	23.71	40.29	37.74
CV (%)	12.01	12.75	10.13	10.59
LSD$_{Tukey}$ α = 0.05	4.74	4.71	4.98	4.88

The effect of gel polymers on the total tuber yield was consistent in both field experiments. The fertiliser-fused gel polymers performed worse in the autumn field experiment. In the spring field experiment, only the total tuber yield in the Aqua3 treatment was statistically equal to that in the control. Plants in the other two fertiliser-fused gel-polymer treatments (Aqua2 and Aqua1.5), however, performed statistically worse than the control.

The pure gel-polymer treatments improved total and marketable fresh tuber yield. In the autumn field experiment, the ST1.5a and ST1.5b treatments increased the total fresh tuber yield by an average of 45% and 25%, respectively. In the spring field experiment, the total fresh tuber yield was improved by 41% in the ST1.5a treatment and by 25% in the ST1.5b treatment.

In both experiments, ST1.5a was statistically superior in marketable tuber yield compared to all the other treatments, except to ST1.5b. The ST1.5b treatment attained an intermediate ranking order between the ST1.5a and Aqua3, but significantly better than the control. In the spring experiment, both the pure gel-polymer treatments, ST1.5a and ST1.5b, performed better than the control and the fertiliser-fused gel-polymer treatments.

There were highly significant differences amongst gel-polymer treatments, and significant interactions between gel-polymer and irrigation treatments for tuber specific gravity. In general, tuber yield and specific gravity showed a negative relationship. The ST1.5a treatment, which performed the best in all tuber yield parameters, achieved the lowest in tuber specific gravity (Fig. 1). To the contrary, Aqua1.5, which performed poorly in all yield parameters, ranked among the treatments that attained the highest specific gravity.
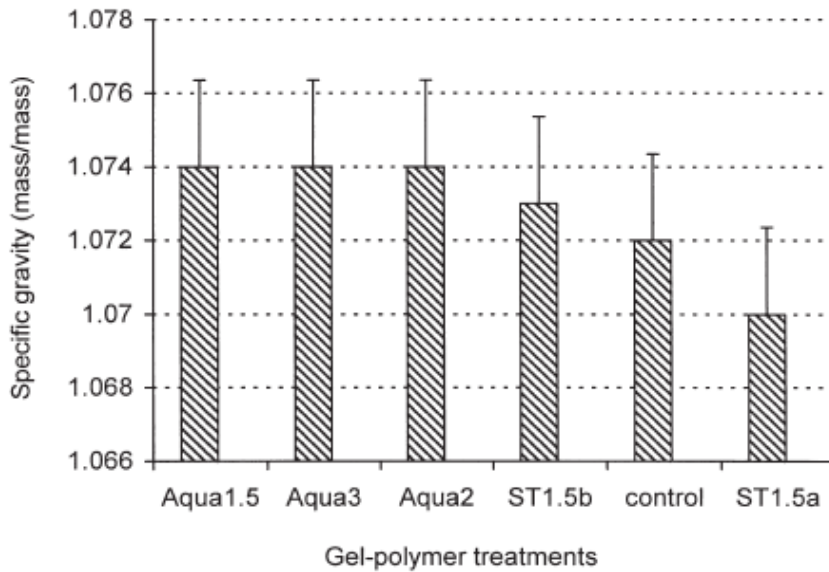
Fig. 1 Response of tuber specific gravity to gel-polymer amendments (the vertical bars represent LSDTukey a = 0.01); control, soil without polymer; Aqua1.5, Aqua2, and Aqua3, fertiliser-fused gel polymer (1.5, 2, and 3 kg/m^3 of soil, respectively); ST1.5a and ST1.5b, pure gel polymer (1.5 kg/m^3 of soil with 85% and 70% respective fertiliser rates).

Similarly, the ST1.5a and ST1.5b treatments scored the lowest specific gravity in almost all moisture depletion levels (Fig. 2). But the general trends of the other treatments showed that specific gravity was reduced as the moisture deficit level increased.
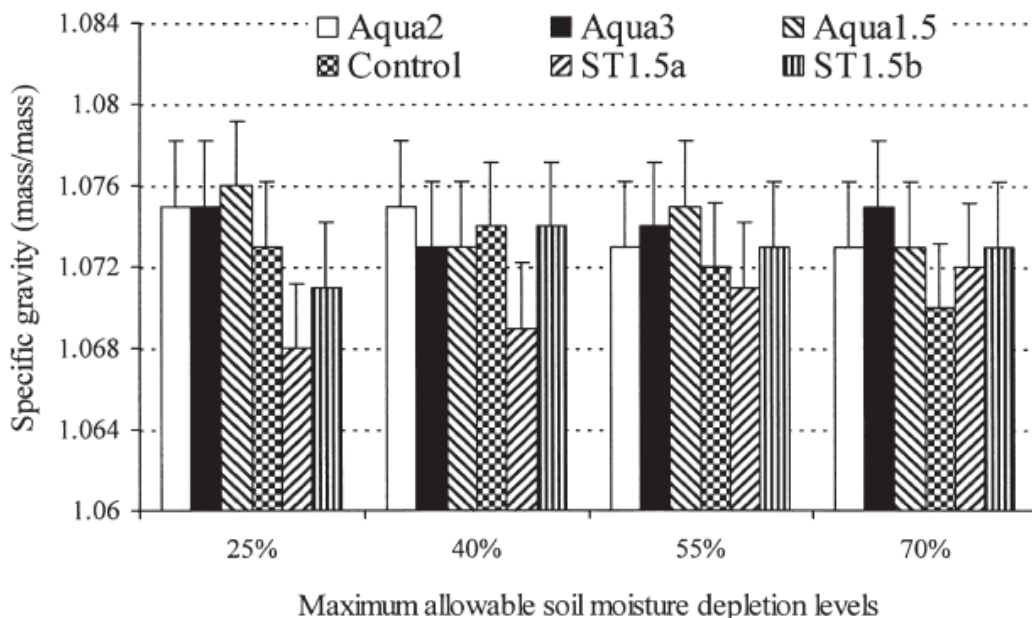

Fig. 2 Response of tuber specific gravity to gel-polymer amendments and irrigation depletion levels in the spring experiment (the vertical bars represent LSD$_{Tukey}$ α = 0.01); control, soil without polymer; Aqua1.5, Aqua2, and Aqua3, fertiliser-fused gel polymer (1.5, 2, and 3 kg/m^3 of soil, respectively); ST1.5a and ST1.5b, pure gel polymer (1.5 kg/m^3 of soil with 85% and 70% respective fertiliser rates).

In the autumn field experiment the gel-polymer soil amendments had no impact on the tuber number; whereas in the spring field experiment, tuber number showed a general declining tendency with an increase in gel-polymer rate (Table 3). However, none of the gel-polymer treatments significantly surpassed the tuber number of the control.

Table 3 Tuber number as affected by gel-polymer treatments in the spring field experiment. Values followed with the same letter in their respective columns are not significantly different from each other at a = 0.05; control, soil without polymer; Aqua1.5, Aqua2, and Aqua3, fertiliser-fused gel polymer (1.5, 2, and 3 kg/m^3 soil, respectively); ST1.5a and ST1.5b, pure gel polymer (1.5 kg/m^3 soil with 85% and 70% respective fertiliser rates).

Treatments	Total tuber no./plant	Marketable tuber no./plant
ST1.5a	9.974 a	7.911 a
ST1.5b	9.926 a	7.832 a
Aqua3	7.872 ab	7.627 a
Control	8.220 ab	6.548 ab
Aqua2	7.783 ab	6.058 ab
Aqua1.5	7.182 b	5.157 b
Grand mean	8.493	6.855
CV (%)	22.86	27.09
LSD$_{Tukey\ \alpha = 0.05}$	2.371	2.266

The impact of moisture regimes on tuber yield was more apparent in the spring field experiment than in the autumn one (Fig. 3). In the autumn experiment, yield showed a declining tendency with an increase in MAD. However, a significant impact of moisture stress (at $\alpha = 0.05$ level) was observed only between the highest MAD level (70% MAD) and the other three MAD levels.
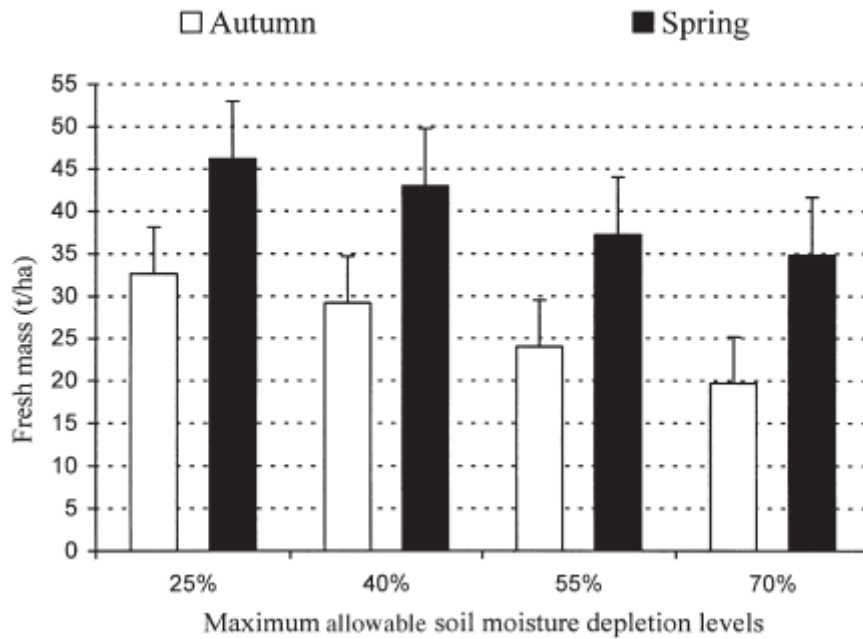
Fig. 3 Total tuber fresh mass in the autumn and spring field experiments: the vertical bars represent LSD$_{Tukey}$ $\alpha = 0.05$ for their respective group means.

In the spring field experiment, incidence of common scab on tubers was not substantial. In the autumn field experiment, however, almost every reduction in maximum allowable soil moisture depletion level caused a significant reduction in the number and mass of degraded tubers (Fig. 4).
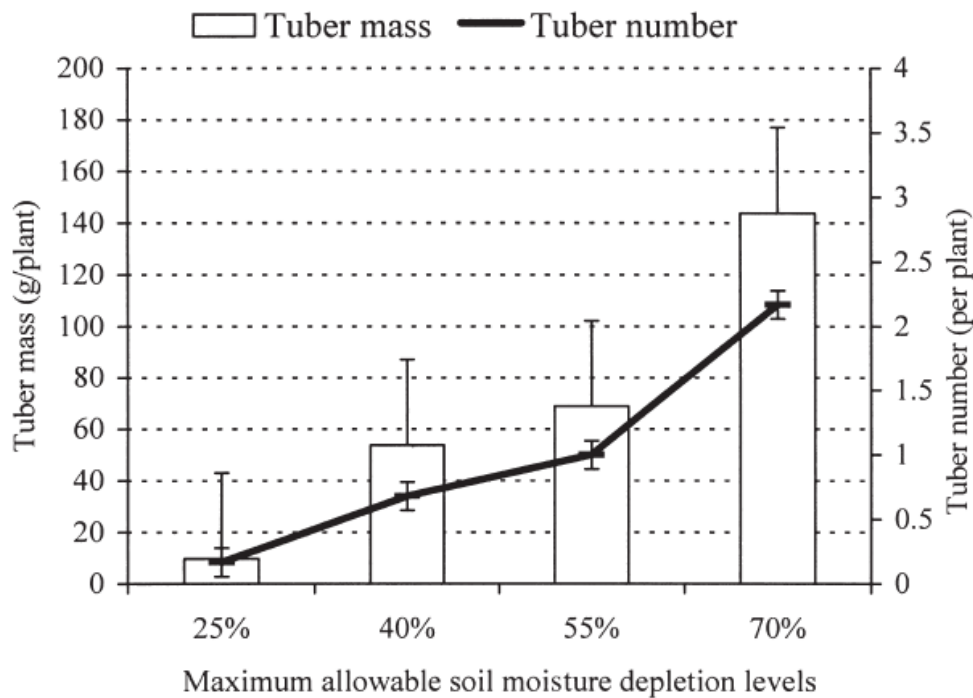

Fig. 4 Number and mass of tubers infected by common scab in the autumn experiment: the vertical bars represent LSD$_{Tukey}$ $\alpha = 0.05$ for their respective means.

DISCUSSION

In general, the total tuber yield performance in the autumn field experiment was very low compared with that of the spring field experiment. Such a difference was, most likely, attributed to the climatic difference in the two seasons: in the autumn the plant experienced hot climate during planting and cold weather towards harvesting, whereas the reverse was true for the experimental plants in the spring. These results suggest that potatoes prefer lower temperatures during tuber initiation and mild to moderate temperatures towards tuber filling (Mohabir & John 1988; Jackson 1999).

The poor performance of fertiliser-fused gel-polymer treatments for all tuber yield parameters contradicted with the hypothesis that the formulation would improve plant growth and yield (van Rooyen et al. 2002). In addition, these results contradict with the higher yield performance expected for a formulation having a high nutrient retention. A preliminary experiment conducted at the University of Pretoria showed that nutrient leaching was lower in the fertiliser-fused gel polymer compared to slow-releasing fertiliser formulations (Anon. 2002). Hence the current result speculates that the low performances of potatoes in the fertiliser-fused gel- polymer formulation were caused by the presence of a lower amount of fertiliser in the root zone compared to the minimum fertiliser demanded by the plants for reasonable tuber yield, and/or the nutrients in the fertiliser-fused gel polymer were not readily available to the plants.

The yield variations observed in the pure gel-polymer treatments in spring and autumn could be explained by the climatic differences experienced in the two seasons. At lower temperatures, the moisture requirement of plants is relatively low (Steyn et al. 1998). Such lower moisture requirements by plants could have affected the contribution of the gel polymer to alleviate moisture stress. In addition, the apparent superiority of the ST1.5a (with higher fertiliser rate) over the ST1.5b (with lower fertiliser rate) suggests that Stockosorb gel polymer would perform better at higher fertiliser rates.

The lower specific gravity of potato tubers in the pure gel-polymer treatments of 25% MAD suggests that both high and low moisture regimes negatively influenced tuber specific gravity. These findings are in agreement with research results reported by Yuan et al. (2003). The authors observed that at higher moisture regimes, the tuber yield was high, whereas the tuber quality in general and specific gravity in particular had deteriorated. Research results reported by Feibert et al. (1994), however, suggested that reduction in specific gravity is not necessarily a concomitant factor in boosting tuber yield. The authors observed that tuber specific gravity of potatoes planted in polyacrylamide (PAM) amended soils was not affected, whereas there was improvement in tuber size and yield.

These results suggest that tuber yield positively responded to soil moisture. Fabeiro et al. (2001) and Yuan et al. (2003) also reported that total volume of applied water and irrigation frequencies significantly affected tuber yield components. The current experimental results suggest the application of moderate deficit irrigation management. It seems that increasing the maximum allowable soil moisture depletion level up to 40% of the available soil moisture would minimise cost and over exploitation of groundwater without significant reduction in the total tuber yield. In

line with the present results, Kashyap & Panda (2003) suggested that scheduling irrigation at 45% of the soil moisture during non-critical growth stages of the potato crop, grown in sandy loam soils, would maximise water use efficiency.

Research has revealed that moisture deficit during tuber initiation and tuber set reduces total tuber number per plant (Costa et al. 1997). Nonetheless, in the current experiments, irrigation depletion levels had no significant impact on total tuber number. The late application of treatments in the current experiments might have led to such results. In terms of marketable tuber number, there were no significant differences among irrigation regimes in the autumn field experiment (data not presented), which could be explained by the lower temperatures and/or light intensity experienced by the plants during most of the tuber-bulking phase. In the spring experiment, tuber number substantially decreased in the two higher irrigation depletion levels. It seems that moisture stress suppressed tuber set number beginning from the early tuber-bulking phase. These results agree with research findings that indicated that moisture stress caused significant reduction in tuber number (Deblonde & Ledent 2001; Yuan et al. 2003).

The response of common scab to maximum allowable soil moisture depletion level, in the autumn experiment, could have been caused by the extended irrigation intervals coupled with higher temperatures during the early tuberisation period in that particular season. This observation supports research reports that suggested moisture stress creates an opportunity for the common scab causative bacterium in bringing about substantial tuber quality degradation (Robinson 1999; Waterer 2002).

In this experiment, the pure gel polymer improved yield of total and marketable tubers. The fertiliser-fused gel polymer did not perform well in most yield parameters. In addition, the results infer that the pure gel-polymer treatments would perform better with relatively higher fertiliser rates. An increase in pure gel-polymer rate reduced tuber specific gravity. Tuber yield parameters negatively responded to maximum allowable moisture depletion levels. The greater total and marketable mass were achieved with the lowest maximum allowable depletion of the plant available moisture. Replenishing the soil moisture when 40% of the plant available moisture is depleted would not bring about significant reduction in tuber yields. The tuber specific gravity was adversely affected by both high and low moisture regimes. Incidence of common scab was inversely related to maximum moisture depletion levels and higher temperatures.

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