Growth and Yield Response of Three Aeroponically Grown Potato Cultivars (*Solanum tuberosum* L.) to Different Electrical Conductivities of Nutrient Solution

Dong Chil Chang · Il Chan Cho · Jong-Taek Suh · Su Jeong Kim · Yong Beom Lee

Abstract The release of two new potato (*Solanum tuberosum* L.) cultivars with different maturing characteristics, Haryeong and Jayoung, necessitates the development of appropriate electrical conductivity (EC) recommendations for the nutrient solutions used in hydroponic seed potato production. The two cultivars, along with the standard cultivar, Superior, were grown with four nutrient solutions differing in EC (0.6, 1.2, 1.8, and 2.4 dS m^{-1}). The EC of nutrient solution did not influence photosynthetic rate (Pr) or water use efficiency (WUE) of leaves, whereas it affected total chlorophyll content, transpiration rate (Tr), and stomatal conductance (Sc) in some cultivars, highest at 0.6 dS m^{-1} EC for Tr and Sc, and lowest at the same EC for total chlorophyll content. The nutrient content of shoots was significantly affected by ECs of the nutrient solution. The total-N content was higher in 2.4 dS m^{-1} EC, whereas a lower P, Ca, and Mg content was measured in plants grown at the same EC. Plants grown with a lower EC had inhibited shoot and stolon growth and earlier tuber formation compared to those grown with higher ECs. For the 0.6 dS m^{-1} EC treatment, tubers were first observed on days 40, 50, and 52 for cvs. Superior, Haryeong, and Jayoung, respectively. For higher EC treatments, tubers were observed 5 to 6 days later, particularly for the new cultivars. At harvest, the number of tubers produced from Superior and Jayoung plants was not affected by EC, whereas those of Haryeong increased at 1.8 dS m^{-1} EC. The results suggest that potato cvs. Superior and Jayoung are able to grow at a wide range of solution EC levels, but that the new cultivar Haryeong needed optimal management of solution EC at 1.8 dS m^{-1} to yield higher tuber production under an aeroponic cultivation system.

Resumen La liberación de dos nuevas variedades de papa (*Solanum tuberosum* L.) con características diferentes de maduración, Haryeong y Jayoung, requiere del desarrollo de recomendaciones apropiadas de conductividad eléctrica (EC) para las soluciones nutritivas usadas en la producción de semilla de papa hidropónica. Las dos variedades, junto con la estándar, Superior, se cultivaron con cuatro soluciones nutritivas que diferían en EC (0.6, 1.2, 1.8, y 2.4 dS m^{-1}). La EC de la solución nutritiva no influenció el nivel fotosintético (Pr) o la eficiencia en el uso del agua (WUE) de las hojas, mientras que sí afectó el contenido total de clorofila, el nivel de transpiración (Tr) y la conductancia estomatal (Sc) en algunas variedades, con la más alta a 0.6 dS m^{-1} EC para Tr y Sc, y la mas baja a la misma EC para el contenido total de clorofila. Se afectó significativamente el contenido de nutrientes en tallos por las ECs de la solución nutritiva. El contenido total de N fue más alto en 2.4 dS m^{-1} de EC, mientras que se detectó un contenido más bajo de P, Ca y Mg en plantas cultivadas a la misma EC. Las plantas en un EC más bajo tuvieron inhibición en el crecimiento de tallo y estolón y formación más temprana de tubérculo comparadas con aquellas que estuvieron en un EC más alto. Para el tratamiento de EC de 0.6 dS m^{-1}, se observaron primero los tubérculos en los días 40, 50, y 52 para las variedades Superior, Haryeong y Jayoung, respectivamente. Para los tratamientos con mayores EC, se observaron los tubérculos de 5 a 6 días más tarde, particularmente para las nuevas variedades. A la cosecha,

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no se afectó por la EC el número de tubérculos producidos de plantas de Superior y Jayoung, mientras que se aumentó en Haryeong a 1.8 dS m^{-1} de EC. Los resultados sugieren que las variedades Superior y Jayoung son capaces de crecer en una gran amplitud de niveles de EC en la solución, pero que la nueva variedad Haryeong necesitó un manejo óptimo de EC en la solución a 1.8 dS m^{-1} para rendir una alta producción de tubérculo bajo un sistema de cultivo aeropónico.

Keywords Haryeong · Jayoung · Mineral content · Photosynthetic rate · Superior · Tuberization

Introduction

Korea has been producing pre-basic potato seed by hydroponic cultivation systems since 1998 (Park et al., 1998). These systems provide demonstrated advantages, including better control of haulm and tuber growth, less labor-intensive harvesting, and higher rates of multiplication. The recommendations for optimum electrical conductivity (EC) ranges for potatoes (*Solanum tuberosum* L.) in hydroponic cultivation systems have been based on the requirements of the Superior cultivar. Previous research (Chang et al., 2005) has demonstrated that plant nutrient concentration, photosynthesis, and optimal response to solution EC differ according to cultivar. The release of new potato cultivars necessitates additional EC research to provide a better understanding of the EC response of these cultivars and to allow development of optimum EC recommendations. Recently, the potato breeding program of the Korean government released several new cultivars, including Haryeong (Park et al., 2006) and Jayoung (Park et al., 2009). Both of these cultivars have morphological and developmental characteristics that differ from Superior. Haryeong is medium maturing, more prone to delayed shoot growth than Superior, and is very resistant to potato late blight (*Phytophthora infestans*). Jayoung, which exhibits purple skins and flesh, is late maturing with susceptibility to late blight. The specific characteristic of each cultivar, along with differences in plant maturity, suggests that each cultivar will have different responses to the EC of nutrient solutions under hydroponic cultivation.

An important cultivation factor studied for hydroponic potato production, EC reflects the total concentration of ions in the nutrient solution. The EC affects nutrient uptake, plant growth, yield, and quality. The total absorption of ions is independent of the EC and is the same in all cases (Sonneveld, 1993). The EC values generally fall between 1.5 and 3 dS m^{-1} for most hydroponic crops (Benoit, 1992). The EC values vary depend on growing season (Chang, 2004), but range from 1.2 (Wheeler, 2006) to 1.7–

2.2 dS m^{-1} (Rolot and Seutin, 1999) in some studies for potatoes. In hydroponic lettuce, solution EC had to be reduced to prevent a rise in tissue nitrate compared to the conditions for rapid growth (Gent, 2003). Hydroponic crops produce strong vegetative growth when EC levels are too high, whereas crops show weak and unproductive growth when EC levels are too low (Barry, 1996). Tomato crops displayed contrasting results; marketable yield was reduced by an increase in blossom end rot with an increase in EC (Sonneveld, 1993), but was increased by a reduction in fruit cracking at the highest EC (Chretien and Gosselin, 2000). Few studies have been published on the effects of EC on potatoes. Our trials were carried out to evaluate the effects of solution EC on the physiological growth response, nutrient absorption, tuberization, and tuber yield by each cultivar.

Materials and Methods

Plant Material and Growing Conditions

This study was designed to determine the interactions between the independent (EC) and the dependent (growth and yields) variables under glass greenhouse conditions at the Highland Agriculture Research Center (HARC), Pyeongchang, Korea (128° 44′ E, 37° 40′ N, and altitude 800-m). Aeroponic culture (Kang et al., 1996) was performed with three cultivars, Superior (mid-early maturing), Haryeong (mid maturing), and Jayoung (late-maturing), with nutrient solutions at four EC levels (0.6, 1.2, 1.8, and 2.4 dS m^{-1}). Each EC was prepared by controlling the mixing ratio of water and stock nutrient solution. A half-strength potato solution (Chang et al., 2000), containing N, P, K, Ca, and Mg at 7.2, 2.1, 3.75, 2.75, and 1.75 me L^{-1}, respectively, as macro-nutrients, and Fe, Mn, B, Zn, Cu, and Mo at 3.0, 0.5, 0.5, 0.05, 0.02, and 0.01 mg L^{-1}, respectively, as micro-nutrients, was used. Each cultivar underwent trials for 2 to 3 years as follows: Superior, from 2008 to 2010; Haryeong, from 2008 to 2009; and Jayoung, from 2009 to 2010.

The EC treatments started 2 weeks after transplanting until harvest except for 2008, wherein the EC treatment was completed 50 days after transplanting (DAT). Plants were periodically sprayed (30-sec duration at 5-min intervals) using eight fog nozzles per 4-m Styrofoam bed. Each nutrient solution was replenished twice a week by manually adding initial nutrient solution to the reservoirs to maintain a constant volume of 200 L. Each time the nutrient solution was replenished, samples were taken after the solution was replenished from each reservoir for an independent measure of pH (Orion 3 Star; Thermo Electron Corp., USA), EC (Orion 3 Star), and nutrient concentrations.

In 2008 and 2009, the initial plant material was obtained by planting 3–5 g of presprouted minitubers (8 months after storage at 4°C and a 4-week presprouting period at 15°C). Healthy and similar sized in vitro plantlets, maintained for 14 days in the greenhouse for acclimatization, were transplanted into each culture bed in 2010. The dates for transplanting into the hydroponic system were September 1, 2008; September 9, 2009; and September 6, 2010. The plantlets were transplanted in two rows per bed with 0.25-m row spacing and 0.25-m planting distances between plants. For the first 30 days, plants grew under a 16-hr photoperiod, including 4 h under artificial lighting after sunset with fluorescent lamps (20 W; Osram). On day 31, the photoperiod was reduced to 12 h by turning off the lamps to promote tuber initiation. Relative humidity and CO_2 levels in the greenhouse ranged between 40% and 70%, and 450 and 530 mg L^{-1}, respectively. A split-plot design with three replications was used, with EC treatment serving as the main plot and cultivars serving as the subplots. Each main plot had 30–60 plants depending on the year, each with 10–20 plants per cultivar. Mean air temperatures in the greenhouse during the growing seasons were 14.1 to 17.7°C with daily mean temperatures ranging between 7.7–13.7 and 20.9–23.6°C.

Growth Response and Nutrient Absorption

The morphological parameters measured were shoot fresh weight, percentage shoot dry matter, stolon length, and tuber initiation. Three plants were sampled at 50 DAT between late October and early November. Shoots were separated for fresh weight determination and then oven-dried at 85°C for more than 48 h for dry weight determination. The percentage of shoot dry matter was calculated as the ratio of dry weight to fresh weight. The longest stolon from each plant was recorded for stolon length. Non-destructive monitoring of tuber appearance started from 30 DAT until full tuberization. Any plant with visible swelling of at least one stolon tip was counted as a tuberized plant (Krauss and Marschner, 1982; Jackson, 1999).

Dried shoots were finely ground in a homogenizer for elemental concentration analyses (Chang et al., 2005). For total-N analysis plant tissues were ashed using the H_2SO_4 method and determination were performed using a Kjeldahl distillation method with an automatic nitrogen analyzer (Vapodest, Gerhardt, Germany). Tissue P was determined using spectrophotometer (Xma 2000; Human Corp., Korea) and K, Ca, and Mg were determined using an inductively coupled plasma spectrometer (Optima 2100 DV; Perkin Elmer, USA) after nitric acid digestion using a microwave digestion labstation (Ethos 1; Milestone SRL, Italy).

Physiological parameters such as photosynthetic rate (Pr), transpiration rate (Tr), and stomatal conductance (Sc) were determined using a photosynthesis system (LI-6400; Li-Cor, Inc., Lincoln, NE, USA) on 30 to 40 days after EC treatment. The Pr, Tr, and Sc were determined on the second or third leaf from the top at 20°C leaf temperature, 1,000 μmol m^{-2} s^{-1} PPFD, and 400 mg L^{-1} CO_2 between 10:00 and 13:00 h KST. Reported values are the means of measurements from each of five stems, at one leaflet per stem. The water use efficiency (WUE) was calculated by dividing the leaf Pr by the leaf Tr (Raviv and Blom, 2001) to understand the relationship between productivity and water use. Chlorophyll contents were analyzed from the same-positioned leaves after extraction with 80% acetone (Chang et al., 2008).

Harvest and Tuber Production

The study crops were harvested on Nov. 27, 2008; Dec. 15, 2009; and Dec. 8, 2010, which were 3 to 7 days earlier or later than the general harvest scheme (90 DAT) in Korea. All tubers larger than 1 g (10–13 mm) in weight were collected at each harvest. The number of tubers per plant, size grade of tubers, and average tuber weight were measured at harvest. Individual tubers were weighed and classified into three groups (1–5 g, 5–30 g, >30 g). Average tuber weight were calculated from the total tuber weight and number of tubers produced per plant.

Statistical Analysis

Statistical analyses were performed using the SAS system (SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) was performed separately for each of the cultivars. The interaction effects between years and EC levels were included in the analysis.

Results and Discussion

Physiological Growth Response

As not all of the three cultivars were tested in the same years, ANOVA was performed for each of the three cultivars as shown in Table 1. Shoot growth was significantly affected by the ECs of nutrient solutions, showing 52% and 68% less growth at 0.6 EC compared to 2.4 EC for cultivars Superior and Haryeong, respectively (Tables 1 and 3). For Jayoung, no difference in shoot growth was observed. Similar results were observed in stolon growth measured as stolon length. Superior and Haryeong displayed the shortest stolon length at 0.6 and 1.2 ECs, whereas did not in cultivar Jayoung (Tables 1 and 3). These

Table 1 Analysis of variance for growth and yield parameters of three aeroponically grown potato cultivars as affected by the electrical conductivities of nutrient solutions

Items	Source	Superior		Haryeong		Jayoung	
		df[z]	MS[y]	df	MS	df	MS
Total chlorophyll	Year	2	0.780***	1	0.050	1	0.284***
	EC[x]	3	0.049	3	0.049	3	0.039*
	EC×Year		0.015		0.006		0.047*
Chlorophyll a/b	Year	2	0.140	1	0.186***	1	0.002
	EC	3	0.022	3	0.020*	3	0.063
	EC×Year		0.020		0.002		0.054
Photosynthetic rate	Year	2	207.5***	1	1,996	1	33.6***
	EC	3	6.6	3	1,354	3	4.1
	EC×Year		9.0		1,174		6.6*
Transpiration rate	Year	2	50.06***	1	16.8***	1	18.9***
	EC	3	0.59**	3	0.1	3	0.1
	EC×Year		0.45*		0.1		0.3*
Water use efficiency	Year	2	44.7***	1	1.32	1	75.3***
	EC	3	0.07	3	0.07	3	0.11
	EC×Year		0.57		0.08		0.25
Stomatal conductance	Year	2	0.32***	1	0.06	1	0.01**
	EC	3	0.02*	3	0.01	3	0.01**
	EC×Year		0.02*		0.00		0.02***
Shoot fresh wt	Year	2	102,217***	1	26,934***	1	1,276
	EC	3	54,194***	3	39,903***	3	4,855
	EC×Year		7,133		2,195		9,322*
% shoot dry matter	Year	2	2.7	1	9.6	1	6.7***
	EC	3	0.5	3	6.5	3	0.8
	EC×Year		0.6		1.1		1.7*
Stolon length	Year	1	635***	1	7,055***	1	31
	EC	3	268**	3	260*	3	63
	EC×Year		42		204*		31
Days to tuber formation	Year	2	247***	1	121***	1	55***
	EC	3	10***	3	44***	3	31**
	EC×Year		14		10*		24**
Tuber fresh wt	Year	2	50,212***	1	210	1	6,237
	EC	3	10,039**	3	11,320	3	4,315
	EC×Year		4,894*		642		189
Mean tuber wt	Year	2	89***	1	14	1	20
	EC	3	4	3	75	3	52
	EC×Year		22***		56		17
Tuber number	Year	2	341***	1	5	1	15
	EC	3	27	3	179***	3	15
	EC×Year		35		36**		43

[z]*df* degree of freedom

[y]*MS* mean square

[x]Electrical conductivity

*,**,***Significant at $p=0.05$, 0.01, and 0.001 levels, respectively

results indicate an earlier tuber formation in the cultivars Superior and Haryeong as a consequence of a lower shoot and stolon growth. Our results reinforce observations that nutrient solution EC generally affects the growth habits of hydroponically grown plants, including potato. High ECs result in vegetative growth at the expense of tuberization, whereas low ECs produce weak plants. Although the percentage shoot dry matter decreased with increasing ECs in the cultivars Superior and Haryeong, there were no significant differences in response of the percentage shoot dry matter to the ECs of nutrient solutions in all cultivars.

The four levels of EC treatment with respect to physiological growth responses, such as total chlorophyll

content, chlorophyll a/b ratio, Pr, Tr, and Sc were compared among the three cultivars (Tables 1 and 2). The nutrient solution EC affected the Tr and Sc of mid-early cultivar Superior leaves, which was highest at 0.6 and 1.2 dS m^{-1} ECs. Haryeong, a mid-maturing cultivar, showed a significant response to the ECs of nutrient solution with respect to chlorophyll a/b ratio, which was lowest at 1.8 dS m^{-1} EC. In the late-maturing cultivar Jayoung, the EC treatment affected the total chlorophyll content and the Sc of leaves, which was lowest at 0.6 dS m^{-1} EC for chlorophyll and highest at the same EC for Sc. Despite the significant differences in Tr and Sc in Superior, Pr expressed on a leaf area basis did not differ significantly among the EC treatments. Thus, Tr and Sc were not limiting the Pr (CO_2 assimilation) of Superior grown in an aeroponic environment, as suggested previously (Chang et al., 2005). Nevertheless, significant variation in terms of tuber growth existed among the EC levels (Tables 1 and 3), representing the differences in total canopy photo-synthesis. Generally, differences in canopy photosynthesis were caused by the differences in shoot growth, such as leaf area index (Bhagsari et al., 1988). In mid- and late-maturing cultivars, however, no significant differences in Pr, Tr, and Sc were found among the EC levels of the nutrient solution, except the Sc for Jayoung. The Sc for Jayoung decreased significantly from 0.52 to 0.45 s cm^{-1}, as in Superior from 0.51 to 0.40 s cm^{-1} (Table 2).

The photosynthetic WUE of potato cultivars was higher in Jayoung (5.2–5.4) and Superior (4.8–5.1) than in Haryeong (3.6–3.8), but was not significantly different among the EC treatments in each cultivar (Tables 1 and 2). Most of the water absorbed by plants is transpired or incorporated into cell organelles (Stern, 1994). The ratio of leaf photosynthesis to leaf transpiration is defined as WUE (Raviv and Blom, 2001). To increase plant productivity, there must be a proportionate increase in transpiration (Burke et al., 1999). Although Haryeong had relatively high Tr, it showed low tuber production (Table 3), possibly due to the low WUE.

Changes of pH and EC, and Nutrient Absorption

It was notable that changes in both pH and EC in nutrient solution were closely dependant on the EC levels of nutrient solution in hydroponic potato production (Fig. 1). The nutrient solution pH decreased to approximately 6.0, 5.5, and 5.0 and then increased to 7.2, 6.8, and 5.8 in the first 3 weeks (30–50 DAT) in 0.6, 1.2, and 1.8 dS m^{-1} ECs, respectively. The pH in 2.4 dS m^{-1} nutrient solution decreased to 4.6 but did not increase during the same period. A similar tendency in nutrient solution pH was observed between 50 and 85 DAT. The decline in nutrient solution pH is striking but not unusual for potatoes in hydroponics. This phenomenon has been observed in a previous study (Chang et al., 2000), but not when the sole source of N is in the nitrate form (Mortley et al., 1993). The presence of N in the ammonium form indicates that potato plants are characterized by a high cation/anion uptake ratio resulting in an efflux of H$^+$ from roots, thus lowering solution pH (Marschner, 1995). Considering that if the pH is between 5.5 and 6.5 all nutrients will be available for absorption in hydroponics (Barry, 1996), the rapid increase in pH above 7 in lower EC treatments (Fig. 1) played a role in triggering mechanisms responsible for the growth retardation of shoots and stolons, and early tuber initiation (Table 3). Our study demonstrates that potato crops can tolerate low pH values induced by high ECs and suffer from K-deficiency at high pH (Harris, 1978) induced by low EC (Fig. 1 and Table 4).

Table 2 Means and standard errors of responses to electrical conductivities of nutrient solution for physiological growth parameters

Cultivar	Electrical conductivity (dS m^{-1})	Total chlorophyll (mg/g FW)	Chlorophyll a/b	Photosynthetic rate[z] (μmol m^{-2} s^{-1})	Transpiration rate[z] (mmol m^{-2} s^{-1})	Water use efficiency (μmol mmol)	Stomatal conductance[z] (s cm^{-1})
Superior	0.6	1.82±0.21[y]	4.23±0.09	20.6±1.9	4.26±1.46	5.54±1.62	0.51±0.13
	1.2	1.84±0.23	4.16±0.10	21.0±2.1	4.27±1.34	5.46±1.38	0.49±0.09
	1.8	1.92±0.16	4.12±0.14	20.1±3.8	4.00±1.53	5.65±1.40	0.44±0.13
	2.4	1.99±0.18	4.24±0.05	19.0±4.1	3.73±1.53	5.64±1.09	0.40±0.14
Haryeong	0.6	1.93±0.01	4.19±0.04	21.1±0.7	5.61±0.56	3.79±0.25	0.63±0.04
	1.2	2.04±0.03	4.10±0.07	20.4±1.1	5.33±0.60	3.87±0.22	0.54±0.04
	1.8	2.14±0.06	4.06±0.07	20.1±1.3	5.54±0.53	3.64±0.11	0.58±0.02
	2.4	2.12±0.04	4.16±0.06	19.6±2.1	5.38±0.69	3.66±0.07	0.57±0.05
Jayoung	0.6	1.67±0.15	4.55±0.07	20.0±0.7	3.81±0.67	5.52±1.18	0.52±0.02
	1.2	1.84±0.10	4.51±0.02	19.8±1.9	3.65±0.44	5.61±1.22	0.49±0.04
	1.8	1.77±0.06	4.35±0.09	18.2±0.0	3.47±0.82	5.69±1.44	0.43±0.07
	2.4	1.84±0.01	4.58±0.02	18.9±0.7	3.56±0.58	5.55±1.14	0.45±0.02

[z] Measuring conditions: 20°C leaf temperature, 1,000 μmol m^{-2} s^{-1} PPFD, and 400 mg L^{-1} CO_2

[y] The values are treatment means±standard errors for 2008, 2009, and 2010

Table 3 Means and standard errors of responses to electrical conductivities of nutrient solution for growth and yield parameters

Cultivar	Electrical conductivity (dS m^{-1})	Shoot fresh wt (g/plant)	Shoot dry matter (%)	Stolon length (cm)	Days to tuber formation	Tuber fresh wt (g/plant)	Mean tuber wt (g)
Superior	0.6	167±37[z]	6.8±0.4	24.1±5.6	40.0±2.1	281±41	9.4±1.2
	1.2	266±96	6.6±0.5	26.2±1.4	40.7±3.5	208±37	8.8±2.0
	1.8	316±90	6.3±0.5	36.1±2.7	41.7±4.3	245±58	8.5±1.6
	2.4	345±44	6.3±0.3	37.1±4.8	42.3±3.6	276±67	9.9±4.3
Haryeong	0.6	91±9	9.8±0.4	49.5±17.8	50.5±0.4	126±8	15.4±0.5
	1.2	180±24	9.3±0.7	47.9±10.9	53.3±1.6	161±8	16.4±1.4
	1.8	233±21	8.0±0.1	62.5±11.8	55.8±1.9	227±3	11.2±0.4
	2.4	281±41	7.7±0.7	52.7±8.0	56.5±2.5	197±5	19.8±3.6
Jayoung	0.6	228±34	6.3±0.1	33.3±1.0	52.3±0.2	193±14	15.6±0.4
	1.2	251±5	6.8±0.5	32.3±0.4	57.0±2.1	189±19	13.0±2.3
	1.8	183±26	6.9±1.0	30.3±0.6	56.9±3.3	134±20	8.5±0.5
	2.4	232±24	6.2±0.6	35.2±0.4	56.5±0.4	174±11	12.6±1.4

[z] The values are treatment means±standard errors for 2008, 2009, and 2010

Nutrient solution EC was relatively stable for the first 3 weeks in the treatment of 1.2 and 1.8 dS m^{-1}. After 50 DAT, the EC increased in higher EC treatments (1.8 and 2.4 dS m^{-1}), indicating relatively more water uptake than nutrients uptake by plants (Syros et al., 2001). The increase in EC, particularly in the late development of plants, could be also attributed to the low availability for nutrients uptake by root senescence (Fig. 2). In the 0.6 dS m^{-1} EC treatment, the nutrient solution EC decreased during the growing season.

Significant nutrient content for cultivars and EC treatment were observed (Table 4). The results indicate that T-N and K contents increased with increased EC, but tissue P, Ca, and Mg contents were reduced at higher ECs, with inducing significant increases in the ratio of T-N to P. Therefore, total-N content was higher at 2.4 dS m^{-1} EC, whereas a lower P, Mg, and particularly Ca content was measured in plants grown at the same EC. The highest contents of tissue Ca and Mg were measured in the plants grown at 0.6 dS m^{-1} EC. It should be noted that solution EC had a considerable effect on the absorption ratio of K to Ca and K to Mg. The total absorption of nutrients was independent of the EC and was almost the same at all ECs.

This trend has been observed in hydroponically grown crops, such as tomato and *Anthurium* (Sonneveld, 1993). Significant EC×cultivar interaction effects were detected in T-N and Ca contents. A previous study also found an increase in T-N and K, and a reduction in P, Ca, and Mg in leaves as EC increased (Chang et al., 2005). In particular, the reduction in Ca and Mg content is considered to be affected by an increase in K uptake, as indicated by Sonneveld (1993).

Figure 2 shows the concentrations of N, P, K, Ca, and Mg in nutrient solution over a period of 2 months after the EC treatment. Persistent accumulation or depletion of particular elements occurred as the solution was replenished by addition of the initial nutrient solution. The high ECs solutions (1.8 and 2.4 dS m^{-1}) showed more accumulation of NO_3-N, K, Ca and Mg. In contrast, each nutrient decreased with depletion in NH_4-N, NO_3-N, PO_4-P, and K under a low EC solution (0.6 dS m^{-1}). In the solution with an EC of 1.2 dS m^{-1}, the concentration of NH_4-N decreased but NO_3-N, PO_4-P, and K maintained at constant levels. Calcium and Mg accumulated in the nutrient solution at the same EC. The EC-dependent solution concentrations of

Fig. 1 The variation with time in the pH and electrical conductivity (EC) of nutrient solutions as affected by the ECs of nutrient solutions. At 50 DAT, each nutrient solution was replaced with fresh nutrient solution. Vertical bars indicate the mean± standard error of three replicates
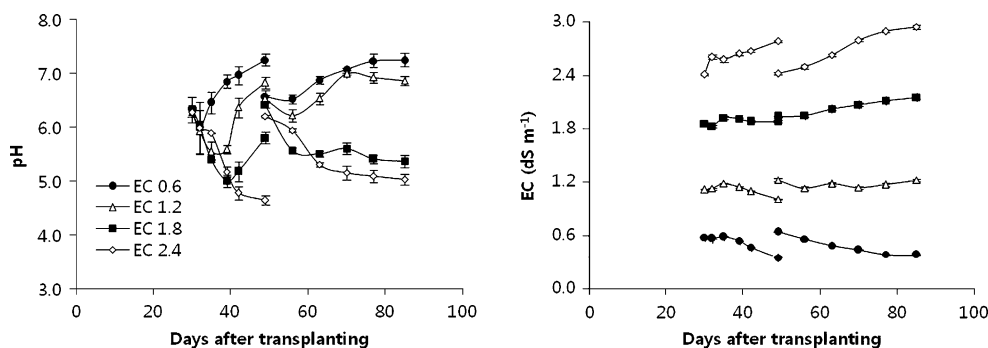
Table 4 Elemental concentrations in the shoots of 50-day-old potato plants grown in nutrient solutions of different electrical conductivities

| Cultivar | Electrical conductivity (dS m^{-1}) | Mineral content (% dwt) | | | | | T-N/P | K/Ca | K/Mg | Ca/Mg |
		T-N	P	K	Ca	Mg				
Superior	0.6	4.2±0.2^z	0.59±0.10	4.71±0.23	2.95±0.13	0. 84±0.06	7.1	1.6	5.6	3.5
	1.2	4.4±0.1	0.51±0.04	5.33±0.18	2.41±0.15	0. 70±0.03	8.7	2.2	7.6	3.4
	1.8	4.6±0.1	0.51±0.03	6.12±0.15	2.17±0.14	0.63±0.03	9.0	2.8	9.7	3.4
	2.4	4.6±0.1	0.53±0.02	5.90±0.19	1.95±0.10	0.60±0.05	8.7	3.0	9.8	3.2
Haryeong	0.6	3.7±0.2	0.60±0.07	2.91±0.33	3.28±0.07	0.70±0.04	6.2	0.9	4.2	4.7
	1.2	4.1±0.1	0.49±0.01	3.79±0.53	2.08±0.14	0.52±0.03	8.4	1.8	7.3	4.0
	1.8	4.6±0.1	0.43±0.03	4.95±0.26	2.29±0.15	0.57±0.03	10.7	2.2	8.7	4.0
	2.4	4.7±0.0	0.40±0.07	4.29±0.16	1.90±0.03	0.50±0.02	11.7	2.3	8.6	3.8
Jayoung	0.6	3.3±0.1	0.64±0.05	3.93±0.15	2.42±0.06	0.73±0.05	5.2	1.6	5.4	3.3
	1.2	3.9±0.1	0.67±0.02	4.32±0.17	2.18±0.17	0.55±0.03	5.9	2.0	7.8	4.0
	1.8	4.2±0.0	0.50±0.02	4.43±0.35	2.31±0.23	0.55±0.07	8.4	1.9	8.0	4.2
	2.4	4.4±0.1	0.51±0.05	4.77±0.43	1.84±0.03	0.55±0.04	8.5	2.6	8.7	3.3
Cultivar		**	*	***	**	***	ns	***	*	***
Electrical conductivity		***	**	***	***	***	**	***	***	*
Cultivar×Electrical conductivity		**	ns	ns	***	ns	*	*	ns	**

^{z} The values are treatment means±standard errors

ns,*,**,*** Non-significant or significant at p=0.05, 0.01, and 0.001 levels, respectively

each nutrient are related to the difference between the supply rate of each nutrient and the uptake rate. In general practice, a concentrated mixture of nutrients is added to hydroponic solution to maintain a certain EC. The nutrients are not adjusted individually, but they are added in fixed proportion. If plants do not absorb a nutrient at the rate in which it is supplied, it will either accumulate or become depleted in the solution (Gent, 2003). Bivalent ions (Ca, Mg and SO$_4$), in particular, accumulate in a recirculating system, and these have a greater influence on the EC than
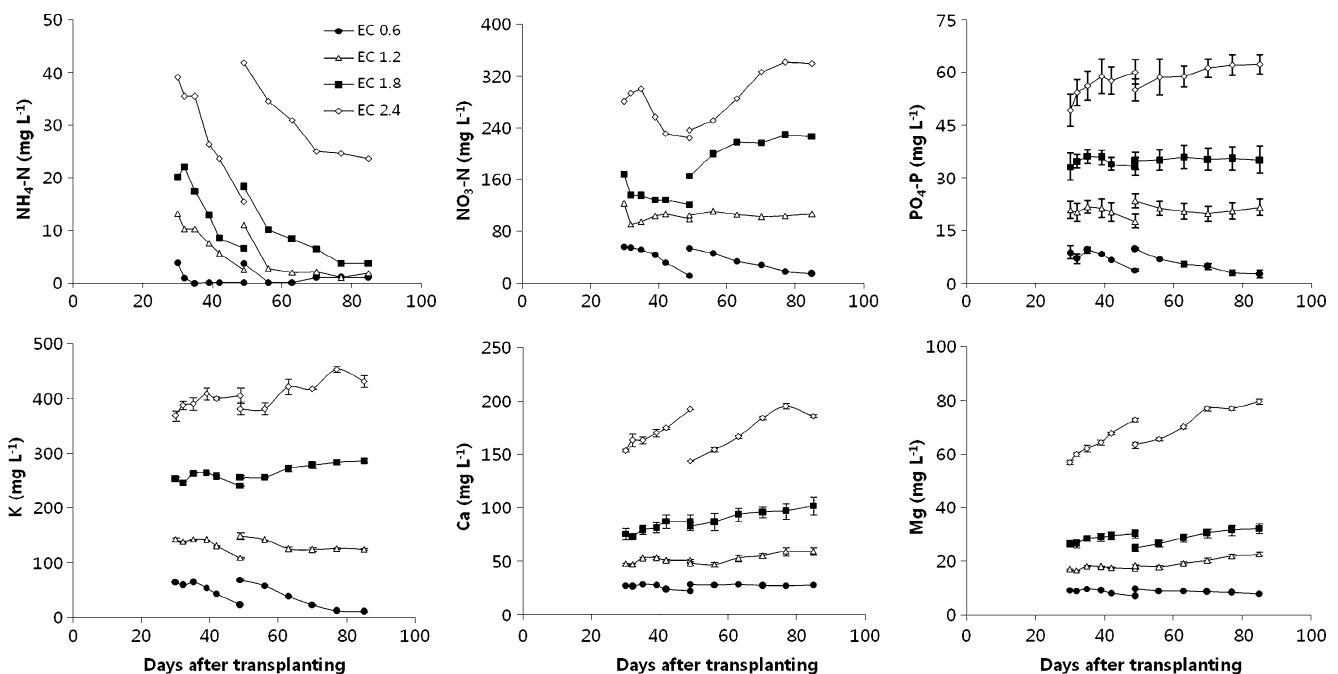

Fig. 2 The variation with time in concentrations of NH$_4$-N, NO$_3$-N, PO$_4$-P, K, Ca and Mg in nutrient solutions as affected by the electrical conductivity of starting nutrient solution. At 50 DAT, each nutrient solution was replaced with fresh nutrient solution. Vertical bars indicate the mean±standard error of three replicates

monovalent ions such as K (Benoit, 1992). The stage of development of the plant also determines outcomes. The data presented in Fig. 2 show that in the vegetative phase, potato plants mainly absorb Ca and Mg for shoot development, whereas during tuber development (after 50 DAT in the figure) they mainly absorbed K, inducing a rapid accumulation of Ca and Mg in the nutrient solution. It has been pointed out that only 6% of the Ca and 41% of the Mg was in the tubers; therefore, for these nutrients, tubers were a less dominant sink than for N, P, and K in the tuber development phase (Harris, 1978). Thus, monitoring of the solution EC as well as pH in the root environment should be conducted as frequently as possible (Benoit, 1992; Barry, 1996).

Days to Tuberization, Tuber Yield, and Size Distribution

Measurements included days to tuber formation, tuber fresh weight, number of tubers produced per plant, and mean tuber weight in each cultivar. There were significant differences among the ECs of nutrient solution in terms of days to tuberization, due to the 2–6 days delayed tuberization at higher ECs (1.8 and 2.4 dS m^{-1}), than at a lower EC (0.6 dS m^{-1}). Jayoung did not show a significant difference in response of days to tuberization to the ECs of nutrient solution in 1.2 to 2.4 dS m^{-1} treatment. For the 0.6 dS m^{-1} EC treatment, tubers were observed first on days 40, 50, and 52 for cvs. Superior, Haryeong, and Jayoung, respectively. For the higher EC treatments, tubers were observed 5 to 6 days later, particularly for the new cultivars. One possible reason for low yields (Table 3 and Fig. 3) is the genetic variation of tuberization rate in the new cultivars. Rolot and Seutin (1999) reported a considerable cultivar response of 8 to 13 tubers in each plant grown in hydroponics. Our results demonstrated that tuberization could readily be manipulated by altering the ECs of the nutrient solution in hydroponic seed potato production, particularly in mid- and late-maturing cultivars such as Haryeong and Jayoung. Many factors have been reported to affect tuber formation, in particular, N levels, temperature, and light, which have the greatest effect (Jackson, 1999). In the present study, high levels of nutrients (particularly N) in nutrient solutions with high ECs are considered the main factor affecting the delayed tuberization (Harris, 1978). This is because potato plants grown in nutrient solutions with higher ECs showed significantly higher contents of T-N (Table 4).

Over 3 years, Superior had the highest tuber yields among the cultivars examined (Table 3 and Fig. 3). Although yield results for Superior were inconsistent among years, the fresh weight of tubers produced significantly increased as EC increased from 1.2 to 2.4 dS m^{-1}. The results of this study also revealed that mean yields for Haryeong and Jayoung were 70.4% and 68.3% that of Superior when grown in
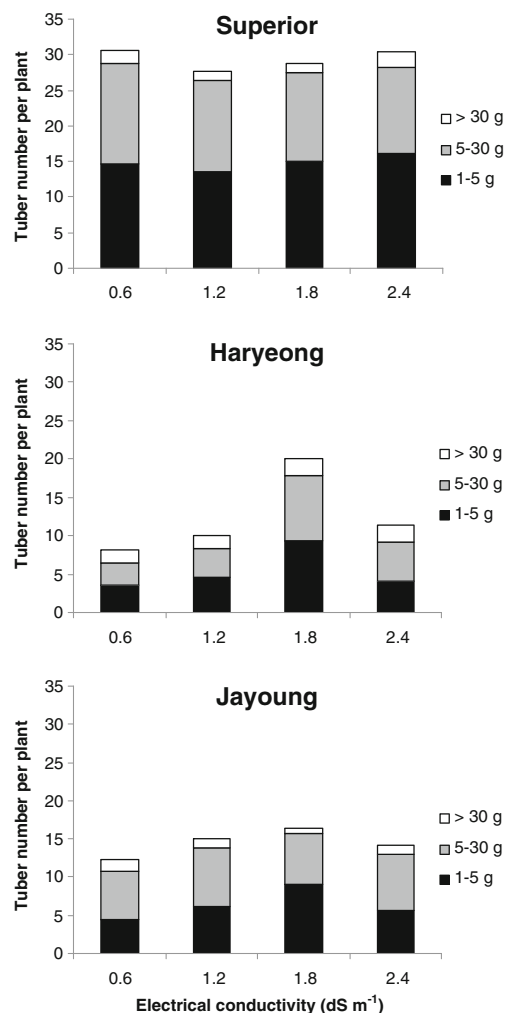

Fig. 3 Tuber number and size distribution of potato plants grown in an aeroponic system as affected by the electrical conductivity of nutrient solutions. Data represent treatment means for 2008, 2009, and 2010

aeroponics. Considering the days to tuberization (Table 3), the growth period for tubers was approximately 35 to 45 days in Haryeong and Jayoung as compared to 50 to 60 days in Superior. Thus, this reduction in the growth period coupled with genetic characteristics resulted in lower yields for the mid- and late-maturing cultivars as compared to the mid-early cultivars. The yield results for the new cultivars revealed no significant difference in tuber fresh weight regardless of ECs. The average number of tubers per plant was also higher in Superior (27.5–31.5) than in Haryeong (8.2–20.4) and Jayoung (12.3–16.0), suggesting that more trials are required to achieve higher yields for these new cultivars. The number of tubers produced from Superior and Jayoung plants was not affected by EC, whereas those of Haryeong were highest at 1.8 dS m^{-1} EC. The results indicate that potato cvs. Superior and Jayoung are able to grow at a wide range of solution EC levels, but the new cultivar Haryeong needed optimal management of solution EC at 1.8 dS m^{-1} to yield higher tuber production under an aeroponic cultivation system.

In field experiments, Haryeong yielded a low volume of marketable tubers under excess fertilization (Chang et al., 2009), justifying the reduction of fertilizer application on Haryeong. This reinforces the generally accepted findings that there is an inverse relationship between haulm growth and tuber growth. If haulm growth is encouraged by the application of early fertilizers, particularly by N, tuber initiation is delayed (Moorby, 1978). At final harvest, mean fresh weight per tuber ranged from 8.5 to 9.9 g for Superior, 11.2 to 19.8 g for Haryeong, and 8.5 to 15.6 g for Jayoung. No significant differences in the mean tuber weight were found in all nutrient solutions differing in EC (Tables 1 and 3). The high mean fresh weight of the new cultivars was attributed to the relatively low number of tubers produced, particularly in the size of 1–5 g and 5–30 g (Fig. 3). The minitubers (1–5 g) are generally planted under greenhouse conditions to improve the field adaptability. The other tubers (5–30 g) are planted as whole tubers under an aphid-proof screenhouse to produce basic seed tubers in Korea (In submission).

The results of the study indicate that regulation of solution EC can be a useful technique for controlling shoot growth and inducing tuberization in potatoes by affecting the composition of the recirculating solution, particularly in mid- or late-maturing cultivars.

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