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The impact of aeration on potato (*Solanum tuberosum* L.) minituber production under soilless conditions

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Aeroponic systems are more effective than hydroponics for minituber production, as provided by the optimal system for root oxygenation. The study was conducted to improve conventional hydroponic systems by applying aeration so as to enhance potato minituber production yield via providing adequate oxygen in the root zone. The responses of Agria and Sante cultivars to different levels of aeration [0 as control, 12.5, 25 and 75% (V_{Air}/V_{media}/min)] were compared, particularly on tuberization and growth characteristics. In both cultivars examined, increasing the level of aeration led to higher number of stolons and tubers. Agria was more responsive and consisted of more large tubers rather than Sante, which influenced the number, yield and dry matter of tubers. Aerated plants had (a) more dry matter in their haulms because of more leaves and shoots, (b) larger leaf areas, and (c) delay in physiological maturity. Higher levels of tuber growth, longer roots and more stolons led to improvements in root: shoot ratio. Leaf area index duration increased remarkably by increased aeration. These features resulted in a remarkable rise in the total minituber number up to 3600/m^2 which were 70% higher compared to the non-aerated group. Moreover, the minituber yield was achieved by applying the moderate level of aeration to 23.9 kg/m^2 in Agria and high level of aeration to 17 kg/m^2 in Sante rather than 8.73 and 6.51 kg/m^2 in the control group, respectively.

Key words: Aeroponics, hydroponics, dissolved oxygen, minituber, potato, tuberization.

INTRODUCTION

There is a great potential for the production of a large number of potato tubers, from potatoes grown in nutrient cultures and bioreactors (Akita and Takayama, 1994; Wurr et al., 1997). During the last decade, applying aeroponic systems in potato minituber production showed remarkable increase in the rate of minituber production. It is claimed that, depending on cultivars, the number of minitubers is between 10000 to 13000 /m^2 with diameters of 12 to 15 mm and weights of 1.5 g (Technico, 2015) in greenhouses. Applying aeroponic system in comparison with bed culture, Tierno et al. (2014) study showed 60 - 80% increase in tuber numbers and 34- 87% higher tuber yield per plant in three potato cultivars. In a recent study, Roosta et al. (2013) compared aeroponic system with hydroponics in three potato cultivars. They reported higher tuber yield (58%) and number of minitubers(277%)

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per plant in aeroponic system when compared to classic hydroponics system. This fact is a milestone in seed potato production.

Considerable yield improvement, favorable germination capability and tuber uniformity in an aeroponic system can be obtained from root availability to water and nutrients, the most important factor, abundant oxygen in the root zone and around the tubers, in conjunction with harvesting interval of uniform tubers during the growing season by the omission of terminal dominance (Farran and Mingo-Castel, 2006; Lommen, 2008; Soffer and Burger, 1988). However, the (a) high cost of installation, (b) maintenance and management, including infrastructure expenditure, (c) complex technology (d) a specialized organization of growers, (e) the lack of buffering, and (f) root zone high humidity which can result in the opening of lenticels and rapid dissemination of contamination have made this system expensive and sensitive for potato minituber production. Indeed, applying aeroponic systems for minituber production encounters challenges worldwide (Mateus-Rodriguez et al., 2013; Mbiyu et al., 2012; Jones, 2005; Millam and Shama, 2007).

In commercial hydroponic conditions, including container systems, root density must increase with decreasing substrate volume in order to compensate for the canopy water and nutrient requirements. The increased root density contributes to greater oxygen and nutrient consumption per unit volume of root zone. Intense root competition, consequently, occurs for oxygen and available nutrients. Simultaneously, the reduced dissolved oxygen (DO) levels can negatively influence the root function; increase their susceptibility to diseases and eventually death (Jones, 2005). Lack of sufficient DO may inhibit ammonium oxidation, leading to pH decrease, accumulation of toxic levels of ammonium in the liquid and even toxic level of ammonium in the gaseous phase of the root zone. Consumption of oxygen by micro-organisms can aggravate this condition owing to decomposition of organic matter. This will provide competition between roots and micro-organisms in absorbing oxygen and leads to more oxygen deficiency in root zone (Boland et al., 2000; Raviv et al., 2008). Frequent solution replenishment with water highly saturated by DO or supplying fresh air in the root zone is likely to minimize the severity of these problems.

Aerobic respiration of roots requires adequate amount of oxygen. Root zone aeration plays an important role in plant growth. Metabolic processes such as cell division, water gradient into the roots and mineral uptake can be inhibited by root oxygen deficiency and may result in changes in root system morphology, nutritional deficiencies and increased water stress (Morard and Silvestre, 1996; Softer et al., 1991).

The comparison of minituber production between aeroponic and hydroponic systems by Roosta et al. (2013), Mbiyu et al. (2012); Factor et al. (2007), and Ritter et al. (2001) demonstrates the superiority of aeroponic systems in potato production. Ritter et al. (2001) emphasized that the annual average for minituber production for aeroponics is almost 70% higher in tuber yield per plant and tuber number is approximately 2.5 folds more than average compared to hydroponic production. Adjusting hydroponic systems with aeroponic characteristics seems critical for increasing the cost effectiveness of the system besides obtaining higher yield in potato minituber production. Therefore, the core purpose of this research was to improve existing hydroponic systems by applying adequate oxygen level in the root zone, in order to enhance potato minituber production yield. In this study, the responses of cultivars to different levels of aeration were compared, in terms of tuberization and growth characteristics.

MATERIALS AND METHODS

This study was conducted in a factorial experiment using randomized complete block design with four replications in order to determine the effect of aeration in rooting medium on potato minituber production in soilless conditions. The involving factors in this experiment included four levels of aeration in the root zone 0 as control, 12.5, 25 and 75% (V_{Air} / V_{media} / min) as well as two commercial cultivars (Agria and Sante). This study was carried out in the glasshouse of Horticulture Science Department in Ferdowsi University of Mashhad, Iran from March to July by applying the close container hydroponic system.

At the bottom of each container (10 l volume with 22.5 cm diameter and 25 cm height) including 8 l media [25%:75% (1:3) composition of perlite and coir], a round air stone was installed that injected fresh air by an air pump to the media via separate flow meters. The flow meters were arranged to allow flowing of 1, 2 and 6 L air per minute, in terms of 12.5, 25 and 75% of the volume of media, respectively. The air pump was equipped with a timer which worked from sunlight to sunset (5:30 to 19:30). Aeration with fresh air was done at four levels, 0 (control), 12.5 (low aeration), 25 (medium aeration) and 75% (high aeration) volume of media per minute. Different levels of aeration were estimated based on DO changes after aeration in the hot time of day (that 2 pm). To obtain adequate number of *in vitro* plantlet, tissue culturing of single nodal cuttings in modified Murashige and Skoog medium (Zamora et al., 1994) was conducted by using virus-free plantlet of ‘Agria’ and ‘Sante’ cultivars.

The three weeks old *in vitro* plantlets were transplanted after one week acclimatization period with 200 plant density/m^2 (Lommen and Struik, 1992) in the composition of perlite and coconut coir. Nutrient solution containing N, P, K, Ca, Mg, S, Fe, B, Cu, Mn, Zn and Mo (182, 41, 300, 200, 48, 158, 3, 1, 0.3, 1.3, 0.3 and 0.07 ppm, respectively) was continuously re-circulated four times per day and replaced every three weeks by changing the amount of N, P and Ca to 100, 141, 180 ppm after stolon initiation and to 60, 180, 160 ppm after tuber initiation, respectively. Also, the pH and electrical conductivity of the solution were maintained at 5.8 and 2.2 to 2.5. Using non-destructive monitoring, the growth characteristics including stem number, plant height, leaf area, stem diameter and DO inside the media were measured at 14, 28, 42, 56, 70, 84, 91 and 105 days after transplanting (DATP) . The estimated leaf area index (LAI) was calculated by correlation between length, width and number of leaves with surface counted from checkered sheet. Oxygen concentration of media was monitored by a Clark-type oxygen meter (Hana, YSI 55-12 USA). Interval harvesting was done in four periods in 42, 70, 91 and 105 DATP (Lommen and Struik,

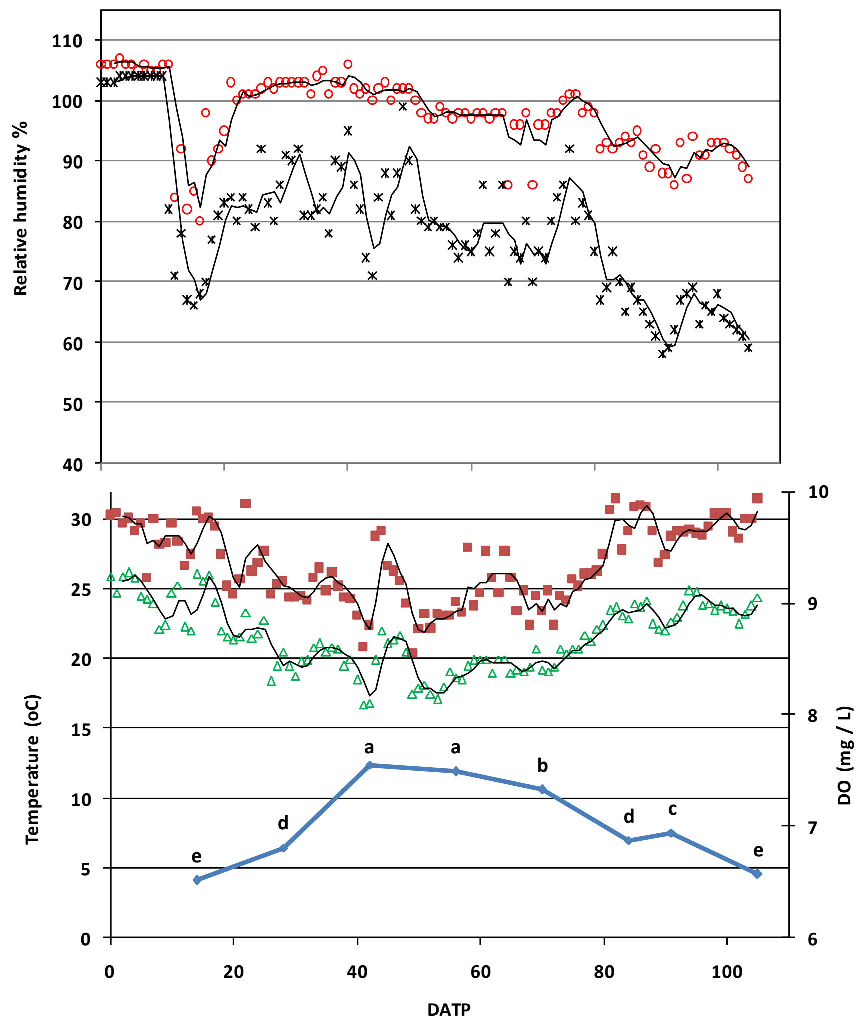

Figure 1. Temperature (■maximum,△ average), humidity (○ maximum, ✱ average) and average dissolved oxygen (-■-) fluctuation during experiment in the greenhouse, equipped with cooling/heating, and moisture regulation systems. Means of dissolved oxygen are significantly different according to Duncan multiple range test, $p < 0.01$.

1992). Root length, number of root and stolon and dry matter of tubers were measured.

Harvested minitubers were classified into four groups according to C_1: <5, C_2: 5 to 10, C_3:10 to 15, C_4: > 15 mm diameter. Fresh weight and dry matter (Oven dried for 72 h at 75°C) of classified minitubers were determined (Simmonds, 1977). The average temperature was maintained between 25°C during day and 17°C at night with 80% relative humidity (RH) in glasshouse under natural light conditions. The data were recorded continually by a computer. Time of tuber initiation was dated when 70% of plants of each plot had at least one tuber (>5 mm diameter). Physiological maturity was assigned when 70% of leaves turned yellow (Kawakami et al., 2004).

To test for field emergence and uniformity of a crop, minitubers (2 minitubers per experimental unit on each class) were dried for two days, cured for 14 days and stored at 4°C in darkness and 80% RH for three weeks. Then they were put in the pre-sprouting condition (15°C, 8 Wm^{-2} light and 80% RH) for 10 days, after treating by 2 ppm gibberellic acid for 10 min in order to break its dormancy. Field planting took place on the loamy soil with drip irrigation. Emergence of three visible leaves was recorded every day. Analysis of variance for all data, orthogonal contrasts and mean comparison was performed by general liner model (SAS Institute Inc., Cary, NC, USA, version 8.2.0).

RESULTS

Environmental condition

This experiment was carried out in a glasshouse equipped with cooling/heating, and moisture regulation systems. However, the temperature and moisture fluctuations during day/night and in the growing season were seen (Figure 1), which usually occurs in the majority of greenhouses. The maximum and minimum temperatures were from 32 to 17°C with the average RH of 80% (59 to 97%). The increment of temperature in the

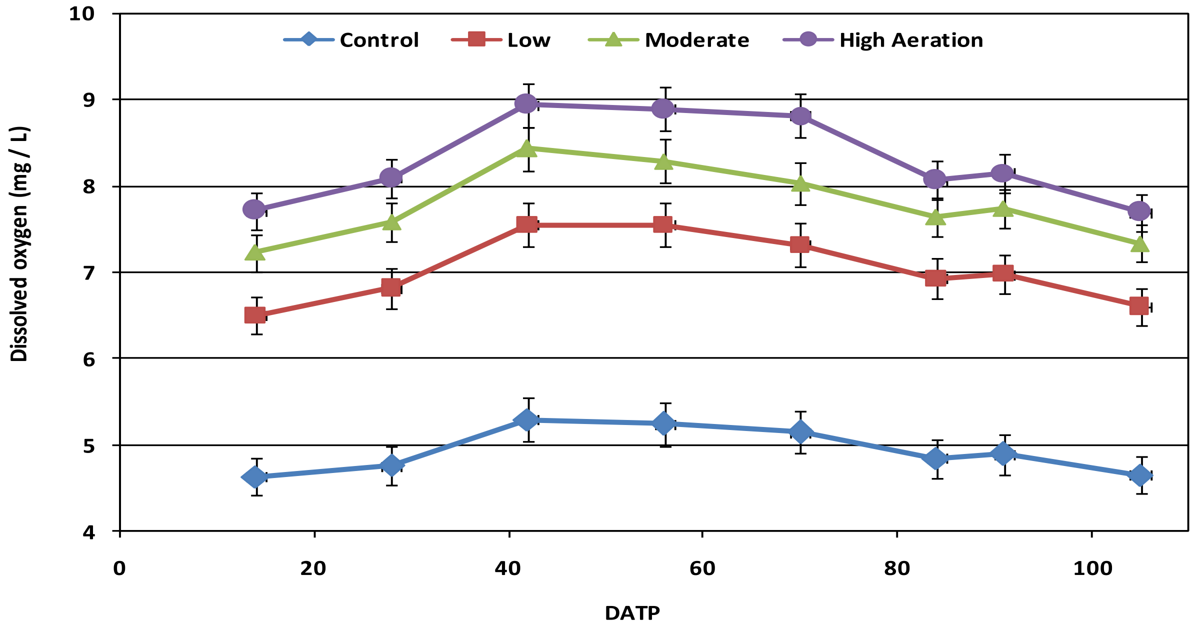

Figure 2. Dissolved oxygen in the media; comparison of different aeration levels (Control = 0, Low = 12.5, Moderate = 25, High = 75% air V/media V min) was significantly different than for the control. Bars indicate standard error, $P < 0.05$.

hot time of day leads to decreasing the level of DO. During sunny days, the radiation rate above the canopy was 15800 lux and during cloudy days, this amount was 7033 lux (27 days) with a photoperiod of 14 h.

Dynamic changes of dissolved oxygen in the root zone

The oxygen concentration of media was measured during the growing season in order to determine the effect of aeration on improvement of DO level in the root zone. Based on Figure 1, the results indicate that the reverse strong correlation between oxygen concentration and the average of temperature fluctuations (R^2= 0.89 P< 0.001) were influenced markedly by applying aeration during the growing season. Moreover, dissimilar levels of aeration, low (12.5% V/min) moderate (25% V/min) and high (75% V/min), illustrated different amounts of DO which ranged from minimum of 4.47 mg/l (~ 41%) to maximum of 9.14 mg/l (~ 95%) in the warm hours of the day (Figure 2).

Plant growth characteristics and performance

Applying aeration in both cultivars (Agria and Sante) resulted in higher vigor, dry weight and leaf area compared to the control. The number of shoots and leaves in each bush were considerably higher in high and moderate levels of aeration compared to the low level and control group. The height of the Agria plant was greater in the high and moderate levels of aeration than the low level and in the control treatment which was the lowest. In *var.* Sante, height of the plant was low in control than aerated levels. The length of the largest root and stolon number were less in the control in both cultivars (Table 1).

Tuberization started simultaneously in all aerated treatments two to three days earlier compared to the control group. The period of tuber induction until the appearance of ripeness, yellowing of leaves, and physiological maturity, increased significantly in treatments with moderate and high levels of aeration. Different levels of aeration influenced significantly stem diameter which is a practical index of vascular diameter and conductivity of sap wood. Higher numbers of leaves and larger leaf area index and the delay in physiological maturity by applying higher levels of aeration were obtained; also, it was found that the leaf area index duration (LAID) increased remarkably by increment in aeration level. All the mentioned characteristics (except starting time for tuberization) were different in both cultivars. This may reflect the different genetic characteristics in these cultivars (Tables 1 and 2).

High level of aeration resulted in 10 and 8 days earlier flowering in Agria and Sante cultivars, respectively in comparison with the control treatment. Physiological maturity occurred 5 to 12 days earlier in the non-aerated treatment. It was revealed that by applying aeration, the growing season was prolonged from 7 to 12 days in *var.* Agria and 5 to 8 days in *var.* Sante compared to the control treatment (Table 2).

Table 1. Effects of different levels of aeration on morphological growth characteristics of potato *var.* Agria and Sante.

Parameter	Stem number per plant		Plant height (cm)		Length of the largest root (cm)		Stolon number per plant		Leaf number per plant		Stem diameter (mm)	
	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante
Control	1.05	0.93	92.1	74.13	23.38	24.11	2.86	3.42	10.6	10.33	4.68	3.8
Low	1.11	1.05	115.92	105.37	41.3	36.56	9.16	6.54	15.27	12.99	6.1	5.13
Moderate	1.34	1.05	127.83	110.58	41.58	33.94	9.7	6.3	18.74	14.96	7.03	5.42
High	1.39	1.12	126.99	105.41	44.7	34.64	9.91	5.68	20.33	14.6	7.58	6.16
LSD 5% (25df)	0.14	0.12	8.77	10.61	8.68	8.96	1.76	1.73	2.21	1.67	0.61	0.5
LSD 1% (25df)	0.2	0.16	11.88	14.36	11.75	12.13	2.38	2.34	3	2.27	0.83	0.67

Aeration levels: Control = 0; low = 12.5; moderate = 25; high = 75 (% air V/media V/ min).

Table 2. Effects of different aeration levels on physiological traits of potato *var.* Agria and *var.* Sante.

Aeration levels	LAI		LAID ($m^2/m^2/day$)		Root/ shoot ratio		HI		DATP to tuberization		DATP to ripeness symptom		Days to emergence		Minituber emergence (%)	
	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante
Control	1.3	1.3	123.6	118.9	1.89	4.31	57.17	70.25	38.13	39.13	92.88	89	5.88	6	85.94	90.63
Low	2.93	2.47	296.1	236.3	3.38	8.29	67.79	80.23	36.63	36.88	100.13	94.38	5	5.63	96.88	92.19
Moderate	4.07	3.23	424.7	315.1	3.05	6.36	67.03	79.29	37.13	37.63	103.5	96.75	4.38	4.75	96.88	98.44
High	4.48	3.53	474.3	347.8	3.42	9.86	71.18	83.02	36.75	36.25	105.13	97.5	4	4.25	96.88	96.88
LSD 5% (25df)	0.29	0.48	30.3	46.7	1.2	4.15	7.24	10.17	1.23	1.66	1.16	2.02	0.39	0.57	6.58	6.87
LSD 1% (25df)	0.39	0.65	41.1	63.3	1.62	5.62	9.79	13.76	1.67	2.25	1.57	2.74	0.53	0.77	8.9	9.3

Aeration levels: Control = 0; low = 12.5; moderate = 25; high = 75 (% air V/media V/ min).

Dry matter accumulation and partitioning

Aerated plants had more dry matter in their haulms due to more existing leaves and shoots because of aeration. In the case of the aerated treatment, a higher level of root growth (especially longer roots, more stolon and dry matter in produced tubers) led to an improvement in root: shoot ratio. A comparison of harvest index (HI) between aerated treatments was also consistent with these results (Table 2).

Figure 3 shows that by applying low and moderate level of aeration, a considerable increase in dry matter in leaves, stem, root and stolon and dry weight of minitubers was observed in *var.* Agria (with more vegetative growth), while in *var.* Sante (with less growth), root and stolon weight did not change significantly. High level of aeration compared to low and moderate level showed no perceivable decrease in dry matter of leaves, stem, root and stolon, except the root weight in Agria which decreased significantly, whereas dry matter of minitubers did not demonstrate any difference with other levels of aeration ($p < 0.05$). It is concluded that *var.* Agria was more responsive to higher aeration than *var.* Sante (Figure 3A and C).

Tuberization and minituber formation

Aeration increased the minituber numbers in class C_4 (diameter > 15 mm), specifically, followed by

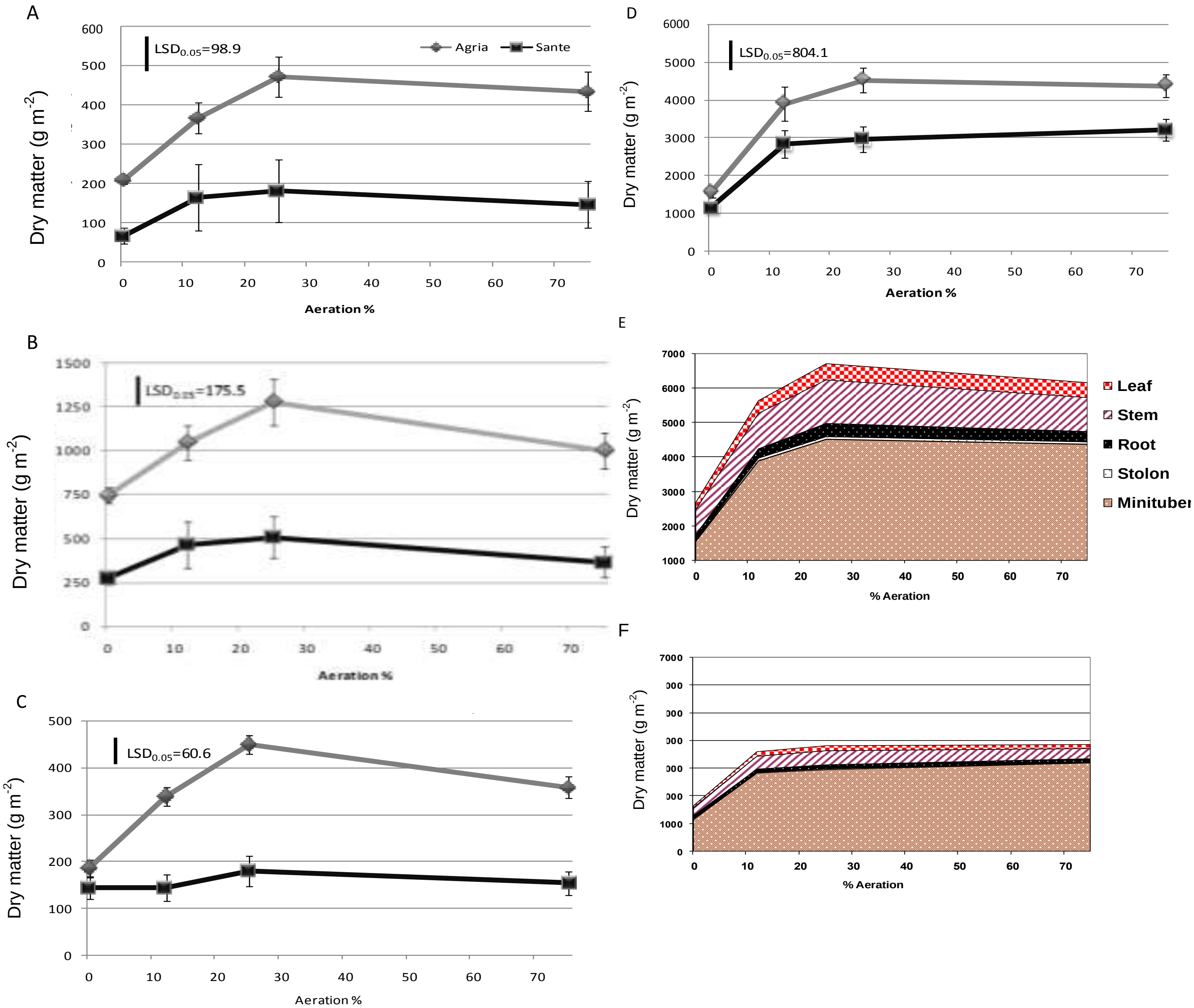

Figure 3. Effect of aeration on dry matter accumulation in different parts of plant, indicating plant biomass partitioning changes in two potato cultivars. **A.** Leaf dry matter. **B.** Stem dry matter. **C.** Root and stolon dry matter. **D.** Minituber dry matter. **E.** Mean of dry matter accumulation in Agria cultivar. **F.** Mean of dry matter accumulation in Sante cultivar% aeration: % air V/media V/ min. Bars indicate standard error, $P < 0.05$.

class C_3 (diameter 10 to 15 mm). The ratio of C_4 and C_1 to total tuber number was 33 and 15% in control treatment, whereas by applying high/moderate level of aeration this ratio was shift to 43.5 and 9%, respectively. Class C_3 of tubers showed an interaction effect between different levels of aeration and cultivars. Orthogonal contrast analysis of minituber numbers in two examined cultivars among different sizes of minitubers demonstrated no significant difference in C_1 and C_2 classes (Figure 4A and B). By increasing the level of aeration, class C_3 showed a sharp rise in the number of minitubers especially in Sante cultivar. The mean of minituber number of both cultivars significantly increased in aerated levels compared to the control group ($p < 0.0001$) and in high and moderate levels of aeration compared with the low level ($p = 0.006$), whereas there was no significant differences between the high and moderate levels of aeration (Figure 4C). Moreover, aeration levels contributed to greater minituber numbers in class C_4 in Agria and Sante which were included 20 and 12 kg/m^2 of tuber yield respectively compared with the control group ($p < 0.0001$). Nevertheless, the different levels of aeration

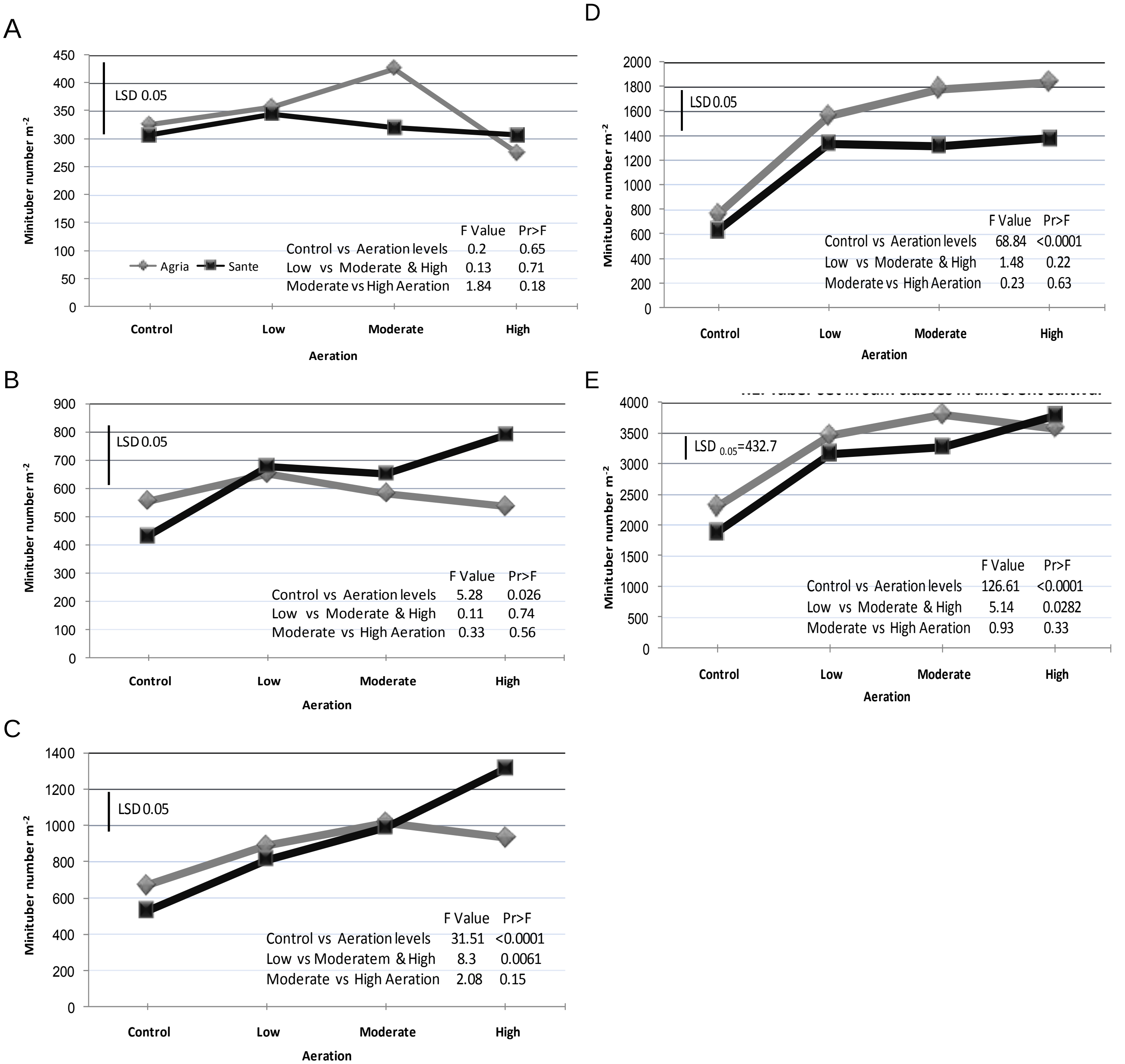

Figure 4. Minituber number of potato plantlet under different levels of aeration and cultivars (Agria, Sante) based on tuber size grading. **A.** Class C1 tuber set in different cultivar. **B.** Class C2 tuber set in different cultivar Class C3 tuber set in different cultivar. **C.** Class C4 tuber set in different cultivar. **D.** Class C1 tuber set in different cultivar. **E.** Tuber set in sum classes in different cultivar. There were more tuber number at class C3 and C4 in all aeration levels versus control. Significant differences in orthogonal contrast were shown in each figure (Pr < 0.5). Bar indicates LSD 5 % for cultivars comparison. Classified groups: C1: <5, C2: 5 to 10, C3:10 to 15, C4: > 15 mm tuber diameter. Aeration levels: control = 0, low = 12.5, moderate = 25, high = 75 (% air V/media V min).

did not show any significant difference in this class (Figure 4D). The results demonstrate that the sum of produced minitubers in these two cultivars significantly increased by aeration ($p < 0.0001$). Although there was no difference between the moderate and high level of aeration, a substantial increase in the number of minitubers was observed in the moderate and high level ($p = 0.028$) compared with the low level of aeration (Figure 4E).

Orthogonal contrast analysis for produced minituber

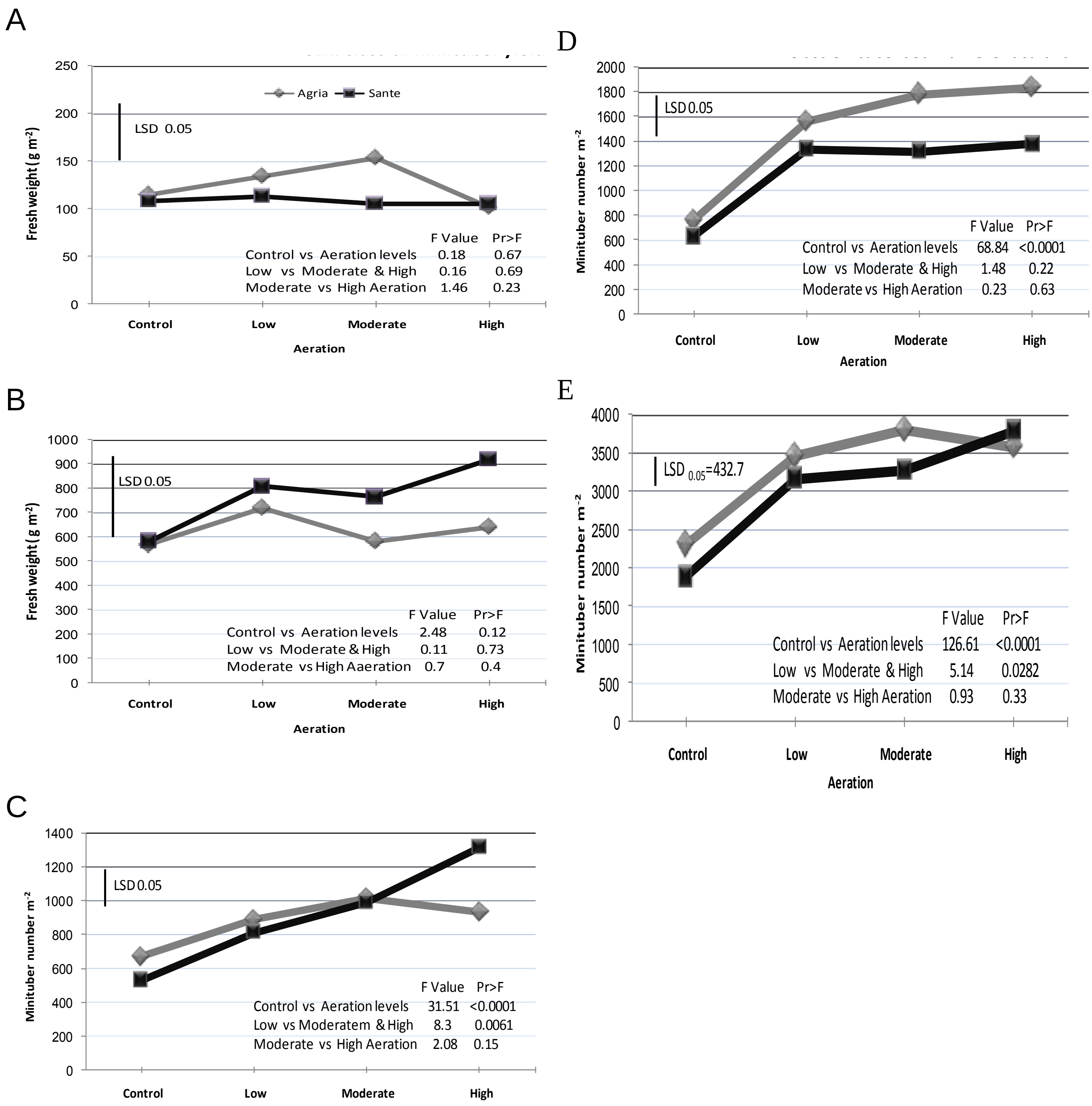

Figure 5. Minituber yield of potato plantlet under different levels of aeration and cultivars (Agria, Sante) based on tuber size grading. **A.** Class C1 minituber yield. **B.** Class C2 minituber yield. **C.** Class C3 minituber yield. **D.** Class C4 minituber yield. **E.** Class C1 minituber yield: Minituber yield in sum classes Larger tuber production (class C3 and C4) occurred by aeration application than control. Significant differences in orthogonal contrast were shown in each figure (Pr < 0.5). Bar indicates LSD 5% for cultivars comparison. Classified groups: C1: <5, C2: 5 to 10, C3:10 to 15, C4: > 15 mm tuber diameter. Aeration levels: control = 0, low = 12.5, moderate = 25, high = 75 (% air V/media V min).

yield indicated that in class C_1 and C_2, minitubers were similar to the number of tubers and were not affected by the aeration (Figure 5A and B), whereas aeration in class C_3, remarkably increased tuber yield compared to the control group ($p < 0.0001$). This difference was considerable between low versus moderate/high levels of aeration ($p = 0.007$). However, high and moderate level of aeration did not lead to any notable difference (Figure

Table 2. Effects of different aeration levels on physiological traits of potato *var.* Agria and *var.* Sante.

Aeration levels	LAI		LAID (m^2/m^2/day)		Root/ shoot ratio		HI		DATP to tuberization		DATP to ripeness symptom		Days to emergence		Minituber emergence (%)	
	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante	Agria	Sante
Control	1.3	1.3	123.6	118.9	1.89	4.31	57.17	70.25	38.13	39.13	92.88	89	5.88	6	85.94	90.63
Low	2.93	2.47	296.1	236.3	3.38	8.29	67.79	80.23	36.63	36.88	100.13	94.38	5	5.63	96.88	92.19
Moderate	4.07	3.23	424.7	315.1	3.05	6.36	67.03	79.29	37.13	37.63	103.5	96.75	4.38	4.75	96.88	98.44
High	4.48	3.53	474.3	347.8	3.42	9.86	71.18	83.02	36.75	36.25	105.13	97.5	4	4.25	96.88	96.88
LSD 5% (25df)	0.29	0.48	30.3	46.7	1.2	4.15	7.24	10.17	1.23	1.66	1.16	2.02	0.39	0.57	6.58	6.87
LSD 1% (25df)	0.39	0.65	41.1	63.3	1.62	5.62	9.79	13.76	1.67	2.25	1.57	2.74	0.53	0.77	8.9	9.3

Aeration levels: Control = 0; low = 12.5; moderate = 25; high = 75 (% air V/media V/ min).

5C). Class C_4, minitubers of more than 15 mm, were affected by different levels of aeration significantly compared to the control group (p <0.0001), whereas there was no difference between different levels of aeration in this regard (Figure 5D). Collectively, in both cultivars and different classes of minitubers, the minituber yield increased appreciably to 23.9 kg/m^2 in Agria and 17 kg/m^2 in Sante by applying aeration (p<0.0001). This increment occurred in high and moderate levels of aeration and was remarkably different (p =0.049) compared to low level of aeration (Figure 5E).

Comparison between the two tested cultivars in this experiment clarified that *var.* Agria, consisted of more class C_4 tubers rather than *var.* Sante due to its special cultivar characteristics, which influenced the number, yield and dry matter of tubers (Figures 4D and 5D) whereas in both cultivars, increasing the level of aeration led to higher number of stolons and tubers especially in the second and third harvest compared to first and fourth harvest. Moreover the minituber yield was achieved by applying the moderate and high level of aeration to 23.9 kg/m^2 in Agria and 17 kg/m^2 in Sante. As a result, their large minitubers (>15 mm) included 20 and 12 kg/m^2 of tuber yield, respectively.

Field emergence test

To ascertain the emergence ability of tubers which were produced under different levels of aeration, pre-sprouted minitubers were planted in a loamy soil. This emergence test proved that all minitubers (86 to 98 %) germinated after four to six days. They were superior in emergence rate for aerated plants than the control, due to higher quality of seeds and the larger tubers which have higher and faster emergence rate (Table 2).

DISCUSSION

Nowadays, container systems are developed commercially for economic and other benefits. Although such systems provide adequate water and nutrients in root zone, they are not so efficient for plants with higher level of oxygen demand in the root zone. These types of plants, due to higher leaf surface and growth velocity, need more active roots to provide water and nutrients for leaves. Desirable performance of aerated plant in this study could be related to higher root oxygen demand of potato that is not affordable by normal ventilation in media. Appropriate oxygen level in root zone promotes the production of larger tubers. On the other hand, potato plant would have more efficient and longer roots with higher number of stolon.

No direct measurement is proven for oxygen deficiency in potato zone. However, it is defined as the concentration of oxygen which inhibits metabolic activities, including cell division, mineral uptake and water movement into roots (Softer et al., 1991). Tuber crops such as potato have a large leaf surface and high production potential consisting of a large biomass underground which has high respiration rate. Oxygen deficiency on hydroponics system is more probable in potato due to the higher demand for oxygen in the root zone (Özkaynak and Samanci, 2006).

In this experiment, temperature fluctuations influenced significantly on the oxygen concentration in the root zone, even in aerated treatments (Figures 1 and 2). Dissolved oxygen decrease was detected (minimum DO = 4.47 mg/l) in the control treatment which led to predictable oxygen deficiency in the root zone.

Consistent with the current experiment, previous studies have depicted the role of aeration in plant yield improvement such as tomato, lettuce, cucumber and melons (Chun and Takakura, 1994; Goto et al., 1996; Bhattaria et al., 2006; Zheng et al., 2007). This role of aeration is facilitated by improving DO concentration. Furthermore, aeration not only offsets hypoxic conditions but also satisfies an unmet demand for oxygen in the root zone (Bhattarai et al., 2006).

According to Zheng et al. (2007), oxygen super-saturation of tomato root zone improves plant performance by oxygen enrichment in nutrition solution, using hydroponic system. Root respiration rates, based on fresh or dry weight, showed a positive linear regression with DO level in the nutrient solution. No changes in dry and fresh weight of plant, stem diameter and leaf area were detected among different treatments from DO = 8.5 to 30 mg/l, due to the short period of their experience (four weeks). Also, Nichols et al. (2002), by growing tomato and cucumber seedlings in an aeroponics system with root zone oxygen ranged from 5 (2 mg/l) to 80% (32 mg/l), clarified that plants' relative growth rates are significantly lower in the treatments with root zone oxygen levels of 5 and 10% than with ambient DO (20%). In lettuce, root browning occurred when DO concentration was as low as 12 mg/l (Chun and Takakura, 1994; Goto et al., 1996). Holtman et al. (2005) showed decreased plant development and reduced root mass, when cucumbers were subjected to the lowest DO (0.5 mg/l). Applying different oxygen levels, escalating differences in leaf area were observed, showing the largest leaf area at 10 mg/l oxygen.

Oxygen in nutrient solution which is seen in the substrates can be completely consumed within 30 min, indicating that roots are very susceptible suffering from anoxia. Oxyfertigation, the injection of pure pressurized oxygen gas to the nutrient solution above saturation levels, has been commercially adapted for use in horticultural greenhouses. Applying oxyfertigation on melon crop, Acuna et al. (2008) claimed higher final yield (quality and quantity) of marketable fruits for oxygen-enriched crops. The oxyfertigation was also described by Marfa et al. (2005) to guarantee root convenience to improve rhizosphere oxygen availability in soilless culture under Mediterranean coastal conditions.

The average tuber numbers of various potato cultivars are 6.2 to 7.9 in plantlets grown in polyethylene bags (Kaur et al., 2000). Lommen and Struik (1992) reported the tuber yield from 16.9 to 23 g and the average tuber number from 8 to 8.8 in two potato cultivars in a glasshouse state (200 plant/m^2). Control group of current research showed similar results. At same plant density, tuber number changed from 1.85 to 2.52 and average tuber weight from 9.8 to 10.9 g, in hydroponics glasshouse conditions (Grigoriadou and Leventakis, 1999). In another study, the tuber yield was 22.95 to 31.23 g, tuber number was from 6.39 to 9.7 and average tuber weight was from 3.36 to 3.63 g in potato plantlets grown under hydroponics glasshouse conditions (Vosátka and Gryndler, 2000). In the result of the present experiment, the maximum yield reached up to 19 tubers per plant weighing 6.3 g, in Agria, by applying the moderate level of aeration. The high level aeration produced 18.9 tubers per plant, weighing 4.5 g, in Sante (Figures 4E and 5E) which explains that aeration requirement might be cultivar dependent.

The results of the current study, regarding yield, biomass production and potato vigor proved that the yield of minituber production was considerably high. Also plants had a longer vegetative period with higher plant height and root length, using a model of aeroponic system. These were consistent with the results of Ritter et al. (2001) and Factor et al. (2007) comparison of hydroponic and aeroponic systems (Table 2).

Diengdoh et al. (2012) point to the size of minituber seed as an important factor for growth and total yield aspects in potato production system. Compared to Lommen (1995) study with 800 plant/m^2 plant density, in the present experiment similar minituber number was produced with plant density 200 plant/m^2 (Figure 4E). Also, applying aeration, the weight and size of tubers increased significantly. This increment resulted in superiority in average minituber number up to 3600/m^2 weighting 5.4 g which was 70% higher compared to non-aeration group. Mateus-Rodríguez et al., (2011) showed that using aeroponics system, the number of minitubers per plant was in the range of 30.6 - 71.7 in three potato cultivars. Tuber yield per plant ranged from 197.6 to 860.2 g per plant within cultivars. Average tuber weight ranged from 6.3 to 12.1 g per minituber. This high variability between cultivars exists as regards their response and production in an aeroponics system under uniform conditions.

The reaction of plant tuberization to aeration which led to increment in size and weight of tubers can be related not only to higher LAID and the preference of aerated plant vigor but also to better root efficiency in water and nutrient absorption (data not shown) due to removal of oxygen deficiency and more efficient respiration inside the tubers in aerobic condition confirming that potato tubers might not tolerate low O_2 concentration. It is concluded that applying aeration leads to a decrease in metabolism and an increase in tuber assimilate (Lipton, 1967).

In another research carried out by Schroeder and Engwicht (2005) on the rose, the growth and productivity was not affected by aeration. It seems that in such plants slighter root biomass, small leaf area and lower optimal growth temperature lead to more resistance to oxygen deficiency. It is concluded that in tuber crops, due to higher oxygen demand especially in tropical area and warm hours of the day, in which the temperature of root zone increases, applying aeration in the root zone can play an important role in improving root requirement and its efficacy. Also aeration and media ventilation results in decreasing harmful gases such as ethylene and ammonium which can affect root growth and activity (Raviv et al., 2008; Weathers and Zobel, 1992).

Relative high temperature in Kang et al. (1996) experiment in tropic area for minituber production systems decreased oxygen solubility, which is related to temperature reversely (Zhang and Shao, 2006). More oxygen in nutrition solution, consequently improved its absorption by the root. In the middle hours of the day when radiation is maximum and a favorable condition for photosynthesis is available, increase in temperature results in a remarkable decline in DO in the root zone (Moore and Townsend, 1998). Therefore, in tropical conditions, oxygen deficiency might be more visible in hydroponic systems. Aeroponic system helps enhancing the solubility of oxygen, via scattering mist in the air. It is suggested that aeroponic system replace hydroponic system if they are equipped with technologies such as aeration or DO super-saturation of nutrition solution that can enhance dissolved oxygen level in the root zone.

Since the present experiment was run at 200 plant/m^2 density, the examined cultivars accomplished up to 3793 minituber/m^2 for Agria and 3781/m^2 for Sante in just 105 days interval that all minitubers grew perfectly in field conditions. For commercial purposes, it can be repeated three times per year; therefore, the annual yield by applying aeration will be more than 10000/m^2 minitubers with 5.4 g weight. This fact is consistent with the claim of professionally minituber production in aeroponic systems. Shortly, it is concluded that applying aeration with suitable level, higher than 25% air V per media V/ min, can improve hydroponic systems toward aeroponics with lower expenditure and much fewer problems.

The overall outcome evidently indicates that hydroponics system with supplementary aeration equipment can be used effectively to amplify the good quantity and quality of minituber production of potato and applying minitubers seems to be a suitable method for large scale use in a seed production program. Yet, minituber production will only be successful if they are economic and in quality superior to other tubers by the existing technologies. Installing aeration system for commercial production needs more investigation. These researches should be related to physical condition of substrate, the place of root dense inside the container and management of root temperature by aeration. By appropriately designing irrigation systems, the pump and tubes can be used alternatively for irrigation and aeration. The greenhouse environment always requires fresh air which is the cheapest and the most vital substance.

Conflict of interests

The authors did not declare any conflict of interest.

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