Effects of paclobutrazol and jasmonic acid on potato minituber production and some plant characteristics in aeroponic cultivation system

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Abstract

In this research, the acclimatized *in vitro* plants were transferred to the aeroponic system and the effects of paclobutrazol (PBZ) and jasmonic acid (JA) were investigated on the production of potato (*Solanum tuberosum* L. cvs Agria and Svalan) minitubers. Some plant characteristics were also investigated in this cultivation system, under greenhouse conditions. Plants were foliar sprayed with PBZ (50 and 100 mgL^{-1}) and JA (5 and 10 mgL^{-1}) 30 and 50 days after transplantation (DAT). Significant interactions were observed between plant growth regulators and the time of foliar spraying for plant height, number of minitubers, and fresh and dry weights of minitubers. Also, the results of the analysis of combined experiments showed significant interactions between cultivars, plant growth regulators, and the time of foliar spraying for the number of minitubers and fresh and dry weights of minitubers. The number, fresh and dry weights of minitubers increased by using 5 mgL^{-1} JA at 30 DAT in cultivar Agria. Also, the use of 5 mgL^{-1} JA at 30 DAT in cultivar Savalan increased the fresh and dry weights of minitubers. The use of 100 mgL^{-1} PBZ caused a reduction in plant height and significantly increased the number, fresh and dry weights of minitubers per plant at 50 DAT in cultivar Agria. In cultivar Savalan, 5 mgL^{-1} JA and 50 mgL^{-1} PBZ significantly increased the number, fresh and dry weights of minitubers per plant at 50 DAT.

Key words: Aeroponic system, Jasmonic acid, Minituber, Paclobutrazol, Potato.

Abbreviations

JA: Jasmonic acid, PBZ: Paclobutrazol, DAT: Days after Transplanting.

INTRODUCTION

Potato (*Solanum tuberosum* L.) is the most important food source in the world after wheat, corn and rice (Manrique, 2000). Production of potato minitubers from *in vitro* plantlets allows a faster multiplication rate in seed production programs (Ranalli, 1997). Minitubers can be currently produced from plantlets which are planted at high-density after acclimatization in greenhouse beds (Wiersema *et al.,* 1987), or in hydroponic system (Rolot and Seutin, 1999). Aeroponic cultivation system was also used successfully for minituber production of potato (Boersig and Wagner 1988; Ritter *et al.,* 2001).

The technique of aeroponic culture is an alternative to the soilless culture method in plant growth controlled environments. The underground organs are enclosed in a dark chamber and supplied with a solution of mineral nutrients with a mist device. Aeroponic system optimizes root aeration and has the major advantage of leading to higher yield compared to classical hydroponics (Soffer and Burger, 1988). Other advantages include the recirculation of nutrient solution, a limited amount of water used, good monitoring of nutrients and pH. This technique has been applied successfully for the production of different horticultural and ornamental species (Molitor and Fischer, 1997; Biddinger *et al.,* 1998). Harvesting in aeroponics is convenient, clean, and allows a better control on the size of minitubers by repeated harvesting (Ritter *et al.,* 2001). Lommen and Struik (1992) showed that the number and time of non-destructive harvests were key factors in the minituber production in aeroponic system. Also, this cultivation system has increased growth and extended the vegetative cycle of potato minituber production between 12% and 36% compared to the plants cultivated in greenhouse beds (Tierno *et al.,* 2014).

Although some authors (Tibbitts and Cao, 1994) reported the delayed tuberization in organs immersed or subjected to continuous mist culture (aeroponics), because of extended vegetative growth (Farran and Mingo-Castel, 2006), tuberization under these conditions could be promoted under definitive stress conditions such as N deficiency (Krauss and Marschner, 1982) and short term reductions in solution pH (Wan *et al.,* 1994).

Potato tuber formation is a process affected by photoperiod, temperature, and other environmental factors and regulated by several plant growth regulators (Hussey and Stacey, 1984; Macháčková *et al.,* 1998; Xu *et al.,* 1998).The endogenous gibberellins are components of the inhibitory signal in potato tuberization under long days. Under short day conditions, gibberellins biosynthesis is reduced and their activity decreases in leaves (Railton and Wareing 1973; Amador *et al.,* 2001). The use of plant growth regulators, particularly growth retardants, may maintain internal hormonal balances and efficient sink-source relationships and thus increase crop productivity (Singh *et al.,* 1987). For the hormonal balance and controlling potato tuberization, some gibberellins biosynthesis inhibitors were used such as 2 -chloroethyl trimethyl ammonium chloride (CCC) (Menzel, 1980), B 995 (Bodlaender and Algra, 1966), and paclobutrazol (Šimko, 1994). Paclobutrazol (PBZ) is a triazole plant growth regulator that blocks GA biosynthesis in plants (Davis *et al.,* 1988). Paclobutrazol has been applied for inhibiting shoot growth in a wide range of plant species (Barrett and Bartuska 1982; Child *et al.,* 1993). Paclobutrazol is an effective plant growth regulator that retards excessive top growth and increases tuber yield as well as quality of potatos grown under conditions of high temperatures and long photoperiod (Tekalign and Hammes, 2004). Qin and Zhang (2010) reported that spraying paclobutrazol could increase stem diameter, potato yield and quality, raise leaf photosynthetic rate and contents of chlorophyll, soluble sugar, starch, and reduce water content. It is hypothesized that PBZ can limit GA biosynthesis in potato and thus improve assimilate partitioning to the tubers (Tekalign and Hammes, 2004).

Jasmonates (JA and its related compounds) are newly recognized growth regulators that are widely distributed in a large number of plant species (Mithöfer *et al.,* 2004). They are involved in various physiological events, including tuber formation and development in potato (Abdala *et al.,* 1996), tuber enlargement in Chinese yam (Koda *et al.,* 1991), bulb formation (Koda, 1997) and its dormancy development (Jásik and de Klerk, 2006) and abiotic stress responses (Wasternack and Hause, 2002). Jasmonic acid (JA), a well-known biological modulator, is reported to be capable of stimulating shoot and bulb formation in garlic (Ravnikar *et al.,* 1993), and inducing *in vitro* tuberization in potato stolons (Pelacho and Mingo-Castel, 1991). Its endogenous presence was confirmed in roots, stolons and periderm of newly formed potato tubers (Abdala *et al.,* 1996). However, a number of studies demonstrated that JA was not directly involved in potato tuberization (Helder *et al.,* 1993; Jackson and Willmitzer, 1994). Ondo Ovono *et al.* (2010) showed that application of exogenous JA at various concentrations positively affected microtuber formation and growth from yam nodal cuttings.

Although some reports have been published concerning the effects of the abovementioned plant growth regulators, the investigations have been on the potato tuber production in the *in vitro*, greenhouse and field natural conditions. Effects of the PBZ and JA have not been investigated on the minituber production in the aeroponic system, to the best of our knowledge. Therefore, in the present study, we aimed to evaluate the effects of Paclobutrazol (50 and 100 mgL^{-1}) and JA (5 and 10 mgL^{-1}) 30 and 50 days after transplanting *in vitro* plantlets of Agria and Savalan cultivars to the aeroponic system.

MATERIALS AND METHODS

Plant material

In vitro potato (*Solanum tuberosum* L.) plantlets of cultivars Agria and Savalan were obtained from nodal explant cultivation in MS medium (Murashige and Skoog, 1962) and acclimatized in a growth chamber at

Table 1. Concentrations of nutrients used in aeroponic cultivation system (mg/L).

Elements	Concentration for the first 35 days	Concentration for the next 35 days	Elements	Concentration for the first 35 days	Concentration for the from 35 days
K	200	250	Fe	1	1
N	190	160	Mn	0.5	0.5
Ca	150	125	B	0.5	0.5
S	70	89	Zn	0.15	0.15
Mg	45	45	Cu	0.1	0.1
P	35	40	Mo	0.05	0.05

Table 2. The average of minimum and maximum temperatures and relative humidity in the greenhouse.

	Minimum humidity (%)	Maximum humidity (%)	Minimum temperature (°C)	Maximum temperature (°C)
Vegetative stage	30.4	44.3	19.1	26
Tuberization stage	44.2	76.5	17	24.4

24 /20 °C (day/night) and 16 h photoperiod during 25 days. Then, uniform plants (about 30 cm height) were transferred to the aeroponic system in a controlled greenhouse.

Aeroponic system

In the present study, a research aeroponic system (phytorhizotron) was used for the production of potato minituber (Movahedi, 2012). This phytorhizotron consisted of two compartments: the upper compartment was supplied with photoperiod control and the lower compartment was kept in darkness. The *in vitro* acclimatized plantlets were cultured on the board of the upper compartment with 13×13 cm spacing and about one-third of the length of the stems was placed inside the lower compartment. Potato shoots grew in the upper compartment that was made of 150×80×120 cm (height×width×length) styrofoam beds. Roots, stolons and minitubers developed in the lower compartment under dark conditions. The lower compartment was a closed container (100×80×120 cm; depth×width×length), which had a removable front panel for monitoring and minituber harvesting. Plant roots were periodically sprayed (every 20 min. for 20 sec.) with nutrient solution using twelve fog nozzles per m^2. Nutrient solution was renewed weekly. Residual nutrient solution flowed back into a collecting tank and was recirculated.

Nutrient solution and growing conditions

Contents of the nutrient solution used are given in Table 1. Solution electrical conductivity (EC) was adjusted to 1.6±0.2 dS/m. The initial pH of the nutrient solution was adjusted to 5.8±0.2 and pH was not controlled afterwards. Plants grew in a glass greenhouse under a 16 h photoperiod for the first 35 days. Then, photoperiod was set to 12 h to promote a quicker minituber initiation. The temperature and relative humidity of the greenhouse were presented in Table 2.

Treatments

Effects of foliar application of PBZ and JA were assessed on the plant growth and development and minituber production of the studied potato cultivars. Control plants were treated with distilled water. In all treatments, 0.05 ml/l Tween 20 was used as wetting agent. Plants were foliar sprayed with PBZ and JA 30 and 50 days after transplantation (DAT) to the aeroponic system. Experimental treatments were factorial in a randomized complete blocks design with three replications. Each replication consisted of three plants. The first factor was plant growth regulator with 5 levels (0 (control), PBZ at 50 and 100 mgL^{-1} and JA at 5 and 10 mgL^{-1}) and the second factor was the time of foliar spraying at 2 levels (30 and 50 DAT).

Data analysis

Considering the advantages of frequent harvests of minitubers in the aeroponic system, in the present study, the minitubers were harvested three times in 10 day-intervals. Potato plants were harvested 100 days after transplantion. Some traits including the plant height, number of nodes, internodes distance, the number of minitubers and fresh weight of minitubers were recorded per plant. To determine the dry weight of minitubers per plant, samples were chopped and dried at 75 °C for 48 h. In each replication, the average for three plants was determined.

Analysis of variance of data was performed using statistical analysis system (Institute 1999). When F

Table 3. Analysis of variance for the effects of plant growth regulators and time of foliar spraying on potato yield and plant characteristics in cultivar Agria.

Source of variation	df	Mean of squares					
		No. of minitubers	Fresh weight of minituber (g)	Dry weight of minituber (g)	Plant height (cm)	No. of nodes	Internode distance (cm)
Replication	2	7.7^{*}	515.12^{ns}	6.12^{ns}	17295.3^{**}	530.9^{**}	1.10^{**}
PGRs	4	6.1^{*}	1163.4^{**}	23.06^{*}	$4497/2^{**}$	109.4^{*}	0.50^{*}
Ti	1	17.7^{**}	3437.05^{**}	103.4^{**}	2199.9^{ns}	8.1^{ns}	1.20^{**}
PGRs×Ti	4	11.7^{**}	1245.5^{**}	25.62^{*}	1593.2^{*}	48.9^{ns}	0.35^{ns}
Error	18	1.8	163.55	5.76	523.9	26.9	0.14
Coefficient of variation (%)		22	21.33	25.66	14.5	12.2	10.3

ns :Non-significant, * and **: Significant at 5% and 1% probability levels, respectively.
PGRs: control, 5 and 10 mg/L JA, 50 and 100 mg/L PBZ.
Ti (time of foliar spraying): 30 and 50 DAT.

was significant at $P<0.05$, the means of treatments were separated by least significant difference test (LSD). Also, analysis of combined experiments was used to analyze the interaction effects among cultivars and plant growth regulators and time of foliar spraying.

RESULTS

Cultivar Agria

Results showed that the PBZ at 50 and 100 mgL^{-1} applied 30 DAT significantly reduced plant height. However, when the treatments were applied at 50 DAT, plant height was significantly reduced only at 100 mgL^{-1} PBZ. The highest plants heights, i.e. 197.5 and 184.5 cm, were obtained by the control plants treated with distilled water at 30 and 50 DAT, respectively. However, there was no significant difference between the control and JA (5 and 10 mgL^{-1}) treatments at both 30 and at 50 DAT (Table 4). The highest number, fresh and dry weights of minitubers per plant were obtained by using 5 mg/L JA at 30 DAT. Also, application of 100 mgL^{-1} PBZ at 50 DAT increased significantly the number, fresh and dry weights of minitubers per plant compared to the control plants (Table 4). In contrast, PBZ treatment applied at 30 DAT reduced significantly the dry weight of minitubers per plant in comparison with the control and other treatments (Table 4). Both PBZ concentrations reduced the number of nodes and internodes distance in comparison with the control plants. Regardless of JA concentration, JA treatment had no significant effect on the number of nodes and internodes distance compared to the control plants (Table 5).

Cultivar Savalan

Results showed that both PBZ concentrations applied at 30 DAT significantly reduced plant height in comparison with the control plants. However, both JA concentrations had no significant effect on plant height. No significant differences were observed in plant height between the control and different concentrations of PBZ and JA at 50 DAT (Table 7).The different concentrations of PBZ and JA at 30 DAT did not show significant effects on the number of minitubers per plant, whereas at 50 DAT, the use of 5 $mgLl^{-1}$ JA and 50 mgL^{-1} PBZ produced the highest number of minitubers per plant (7.2 and 6.9, respectively) (Table 7). The concentration of 5 mgL^{-1} JA at 30 DAT significantly increased fresh weight (51.8 g) and dry weight of minitubers per plant (6.5 g). The lowest dry weight of minitubers per plant was obtained by using 100 mgL^{-1} PBZ at 30 DAT. In contrast, 50 mgL^{-1} PBZ and also 5 and 10 mgL^{-1} JA applied at 50 DAT significantly increased the fresh weight of minitubers per plant (Table 7). The concentrations of 5 mgL^{-1} JA and 50 mgL^{-1} PBZ produced significantly the highest dry weight of minitubers per plant (9.9 and 11 g, respectively) (Table 7). The use of 100 mgL^{-1} PBZ reduced number of nodes/plant, even though no significant difference was observed between the other treatments (Table 8).

Analysis of combined experiments

A significant interactions between cultivars, plant growth regulators and time of treatments application were observed for the number and fresh and dry weights of minitubers. Also, significant interactions were observed between plant growth regulators and time of treatments application for plant height, number of nodes and internodes distance traits (Table 9). The use of 100 mgL^{-1} PBZ at 30 DAT significantly reduced plant height and the number of nodes in comparison with the other

Table 4. Effects of plant growth regulators and time of foliar spraying on yield and plant characteristics in cultivar Agria.

Treatment	30 DAT				50 DAT			
	Plant height (cm)	No. of minitubers	Fresh weight of minituber (g)	Dry weight of minituber (g)	Plant height (cm)	No. of minitubers	Fresh weight of minituber (g)	Dry weight of minituber (g)
Control (H_2O)	197.5^{a}	4.5^{b}	47.9^{b}	8.3^{b}	184.5^{a}	5.1^{b}	58.1^{b}	9.1^{b}
Ja (5 mgL^{-1})	172.0^{ab}	8.3^{a}	86.9^{a}	12.7^{a}	167.4^{ab}	6.3^{b}	70.8^{b}	12.1^{ab}
Ja (10 mgL^{-1})	169.0^{ab}	5.1^{b}	48.9^{b}	7.2^{b}	171.3^{ab}	6.7^{ab}	73.6^{b}	12.3^{ab}
PBZ (50 mgL^{-1})	105.5^{c}	4.7^{b}	29.2^{b}	5.4^{b}	160.7^{ab}	6.6^{ab}	53.8^{b}	8.8^{b}
PBZ (100 mgL^{-1})	101.2^{c}	4.1^{b}	33.3^{b}	3.9^{c}	149.7^{b}	9.8^{a}	96.9^{a}	13.8^{a}

Means of the same column sharing the same letters are not significantly different ($p<0.05$).
JA: jasmonic acid.
PBZ: paclobutrazol.

Table 5. Effect of plant growth regulators on the number of nodes and internodes distance in cultivar Agria.

Treatment	No. of nodes	Internodes distance (cm)
Control (H_2O)	46.3^{a}	4.1^{a}
JA (5 mgL^{-1})	44.0^{ab}	3.8^{ab}
JA (10 mgL^{-1})	45.9^{a}	3.6^{ab}
PBZ (50 mgL^{-1})	38.1^{bc}	3.4^{b}
PBZ (100 mgL^{-1})	37.5^{c}	3.3^{b}

Means of the same column sharing the same letters are not significantly different ($p<0.05$).
JA: jasmonic acid.
PBZ: paclobutrazol.

Table 6. Analysis of variance for the effects of plant growth regulators and time of foliar spraying on potato yield and plant characteristics in cultivar Savalan.

Source of variation	df	Mean of squares					
		No. of minitubers	Fresh weight of minituber (g)	Dry weight of minituber (g)	Plant height (cm)	No. of nodes	Internodes distance(cm)
Replication	2	7.4**	1982.8**	14.9**	29516**	896.9**	2.9**
PGRs	4	7.8**	894.7**	18.4**	2209.6**	43.4^{ns}	0.5^{ns}
Ti	1	3^{ns}	1840.7**	35.9*	606.6^{ns}	56.9^{ns}	2.2**
PGRs×Ti	4	1.5^{ns}	385.3**	19.1**	1402.3**	39.6^{ns}	0.7^{ns}
Error	18	1.05	83.24	1.7	193.6	22.2	0.25
Coefficient of variation (%)		19.5	22.2	22.7	9.9	12.2	13.9

ns: Non-significant; * and **: significant at 5% and 1% probability levels, respectively.
PGRs: control, 5 and 10 mg/L JA, 50 and 100 mg/L PBZ.
Ti: time of foliar spraying (30 and 50 DAT).

Table 7. Effects of plant growth regulators and time of foliar spraying on yield and plant characteristics in cultivar Savalan.

Treatment	30 DAT				50 DAT			
	Plant height (cm)	No. of minitubers	Fresh weight of minituber (g)	Dry weight of minituber (g)	Plant height (cm)	No. of minitubers	Fresh weight of minituber (g)	Dry weight of minituber (g)
Control (H_2O)	157.60^{a}	4^{a}	31.3^{b}	4.7^{b}	150.0^{a}	3.6^{c}	25.7^{b}	3.4^{c}
JA (5 mgL^{-1})	166.80^{a}	5.9^{a}	51.8^{a}	6.5^{a}	155.7^{a}	7.2^{a}	62.2^{a}	9.9^{a}
JA (10 mgL^{-1})	149.80^{ab}	5.7^{a}	34.3^{b}	6.02^{a}	130.8^{a}	5.6^{ab}	56.1^{a}	8.4^{b}
PBZ (50 mgL^{-1})	115.50^{b}	4.9^{a}	26.8^{b}	4.2^{b}	147.3^{a}	6.9^{a}	64.9^{a}	11^{a}
PBZ (100 mgL^{-1})	87.03^{b}	4.2^{a}	22.2^{b}	3.6^{c}	138.0^{a}	4.5^{bc}	35.9^{b}	5.4^{bc}

Means of the same column sharing the same letters are not significantly different ($p<0.05$).

Table 8. Effects of plant growth regulators on the number of nodes in cultivar Savalan.

Treatment	No. of nodes
Control (H_2O)	39.45^{a}
JA (5 mgL^{-1})	42.23^{a}
JA (10 mgL^{-1})	37.13^{ab}
PBZ (50 mgL^{-1})	38.97^{a}
PBZ (100 mgL^{-1})	35.03^{b}

Means of the same column sharing the same letters are not significantly different ($p< 0.05$).
JA: jasmonic acid.
PBZ: paclobutrazol.

Table 9. Analysis of combined experiments for the effects of cultivar, plant growth regulators, and time of foliar spraying on potato yield and plant characteristics.

Source of variation	df	Mean of squares					
		No. of minitubers	Fresh weight of minituber (g)	Dry weight of minituber (g)	Plant height (cm)	No. of nodes	Internodes distance (cm)
Cultivar(CV)	1	11.2^{ns}	5364.6^{ns}	197.2^{*}	4724.2^{ns}	218.7^{ns}	0.14
Rep (CV)	4	7.6	1660.6	10.5	23405	714	2.01
PGRs	4	10.5^{**}	1368.4^{**}	24.9^{**}	5878.2^{**}	106.2^{**}	0.95^{**}
Ti	1	17.7^{**}	5209.9^{**}	130.6^{**}	2558.4^{*}	11^{ns}	3.32^{**}
PGRs × Ti	4	5.9^{**}	968.5^{**}	15.6^{**}	2921.4^{**}	40.5^{ns}	0.8^{**}
CV × PGRs	4	3.4^{ns}	666.2^{**}	16.6^{**}	828.6^{ns}	46.5^{ns}	0.09
CV × Ti	1	3.1^{ns}	115.1^{ns}	8.7^{ns}	248.1^{ns}	53.8^{ns}	0.06
CV × Ti × PGRs	4	7.3^{*}	658.7^{**}	29.2^{**}	74.1^{ns}	48.1^{ns}	0.22
Error b	36	1.4	149.7	3.7	358.7	24.6	0.2
Coefficient of variation (%)		21.1	24.2	25.6	12.7	12.2	12.2

ns: Non-significant; * and **significant at 5% and 1% probability levels, respectively.
PGRs: control, 5 and 10 mg/L JA, 50 and 100 mg/L PBZ.
Ti: time of foliar spraying (at 30 and 50 DAT).

Table 10. Effects of plant growth regulators and time of foliar spraying on yield and plant characteristics in analysis of combined experiments.

Treatment	30 DAT			50 DAT		
	Plant height (cm)	No. of nodes	Internodes distance (cm)	Plant height (cm)	No. of nodes	Internodes distance (cm)
Control (H_2O)	177.5[a]	45.1[a]	3.9[a]	167.2[a]	40.7[a]	4.05[a]
JA (5 mgL^{-1})	169.4[a]	43.7[ab]	3.8[a]	160.2[a]	42.6[a]	3.7[a]
JA (10 mgL^{-1})	159.4[a]	43.5[ab]	3.5[a]	151.1[a]	39.6[a]	3.8[a]
PBZ (50 mgL^{-1})	110.5[b]	38.2[b]	2.9[b]	148.5[a]	38.8[a]	3.8[a]
PBZ (100 mgL^{-1})	94.1[c]	34[c]	2.8[b]	149.3[a]	38.5[a]	3.8[a]

Means of the same column sharing the same letters are not significantly different ($p < 0.05$)

treatment combinations. PBZ treatments significantly reduced the internodes distance in comparison with other treatment combinations. However, no significant differences were observed between plant growth regulators and time of foliar spraying at 50 DAT (Table 10). The use of 5 mgL^{-1} JA at 30 DAT produced the highest number of minitubers and also fresh and dry weights of minitubers in cultivar Agria. However, the use of 100 mgL^{-1} PBZ at 50 DAT produced the highest number of minitubers and also fresh and dry weights of minitubers in cultivar Agria. Regardless of time of foliar spraying, the lowest number of minitubers was obtained in the control plants of cultivar Savalan (Table 11). Eventually, in both cultivars and times of foliar spraying, no significant differences were observed between the control plants for the number of minitubers per plant (Table 12). Regardless of time of foliar spraying, the fresh and dry weights of minitubers of the control plants of cultivar Agria were higher than those of cultivar Savalan (Table 12). The use of 5 mgL^{-1} JA at 30 DAT in cultivar Savalan reduced the fresh and dry weights of minitubers in comparison with the other treatment combinations. Regardless of time of foliar spraying, 10 mgL^{-1} JA reduced the dry weight of minitubers in cultivar Savalan compared to cultivar Agria. Also, regardless of the cultivar used, 50 mgL^{-1} PBZ applied at 50 DAT significantly increased the number of minitubers and also fresh and dry weights of minitubers per plant. However, 100 mgL^{-1} PBZ at 50 DAT in cultivar Agria significantly increased the number and fresh and dry weights of minitubers, whereas no significant differences were observed between the other treatment combinations (Table 12).

DISCUSSION

Aeroponic system can be a usable option for developing countries if minimal conditions are met. Mateus-Rodriguez *et al*. (2013) showed that aeroponics system makes it possible to improve production efficiency and reduce costs compared with conventional methods or hydroponics-based techniques in Latin America. Aeroponics is a good choice for all companies or institutions with experience in potato minituber production. In aeroponic system, the number of potato minitubers could be increased two to three times greater than the traditional methods (Rykaczewska, 2016). Our results also showed that the aeroponic system is a viable technological alternative for the potato minituber production and that the cultivar played a significant role in the number of tubers formed.

Like rooting and flowering (Gaspar *et al.,* 1996), tuber formation is also under hormonal control. There are different reports describing the importance of gibberellins and paclobutrazol (Bandara *et al.,* 1998; Nivedithadevi *et al*., 2012), cytokinins, jasmonic acid and abscisic acid in potato tuber induction (Ondo Ovono, 2010). Triazoles are potent plant growth regulators that have been used to retard shoot growth and promote tuber growth at low concentrations. Paclobutrazol has effectively inhibited growth of different plant species including potato (Tekalign and Hammes, 2004), *Dianthus caryophyllus* (Banon *et al.,* 2002) and Scaevola (Terri and Millie, 2000). Tekalign and Hammes (2004) reported that the most noticeable potato growth response to PBZ treatment as foliar spray and soil drenching are reduction in shoot growth. As a result, treated plants were short and compact due to reduced stem elongation and leaf area. This phenomenon was related to reduced gibberellins synthesis in response to PBZ treatment, resulting in a reduction in cell proliferation, thus, reduction in leaf expansion (Tekalign and Hammes, 2004). Lim *et al.* (2004) reported that the higher concentration of PBZ produced the lower plant height and, in contrast, the higher concentrations of GA_3 increased the higher plant height in both tested cultivars. In the present study, no

Table 11. Interactive effects of cultivar, plant growth regulators, and time of foliar spraying on potato yield and plant characteristics.

Cultivar	Plant growth regulators	30 DAT			50 DAT		
		No. of minitubers	Fresh weight of minituber (g)	Dry weight of minituber (g)	No. of minitubers	Fresh weight of Minituber (g)	Dry weight of minituber (g)
Agria	Control (H_2O)	4.5^{bc}	47.9^{b}	8.3^{ab}	5.1^{cd}	58.1^{b}	9.11^{b}
	JA (5 mgL^{-1})	8.3^{a}	86.9^{a}	12.7^{a}	6.3^{bcd}	70.8^{ab}	12.1^{ab}
	JA (10 mgL^{-1})	5.1^{bc}	48.9^{b}	7.2b^{c}	6.7^{abc}	73.6^{ab}	12.3^{ab}
	PBZ (50 mgL^{-1})	4.7^{bc}	29.2^{c}	5.4^{bcd}	6.6^{abc}	53.8^{b}	8.8^{b}
	PBZ (100 mgL^{-1})	4.1^{bc}	33.5^{bc}	3.9^{cd}	9.8^{a}	96.9^{a}	13.8^{a}
Savalan	Control (H_2O)	4.0^{c}	31.3^{c}	4.7^{cd}	3.6^{e}	25.7^{c}	3.4^{d}
	JA (5 mgL^{-1})	5.9^{b}	50.8^{b}	4.7^{cd}	7.2^{ab}	62.2^{b}	9.9^{ab}
	JA (10 mgL^{-1})	5.7^{b}	34.3^{bc}	6^{bcd}	5.6^{bcd}	56.1^{b}	5.7^{c}
	PBZ (50 mgL^{-1})	4.9^{bc}	26.8^{c}	4.2^{cd}	6.9^{abc}	64.9^{b}	11.0^{ab}
	PBZ (100 mgL^{-1})	4.1^{bc}	22.2^{c}	3.6^{d}	4.5^{de}	36.0^{c}	4.1^{cd}

Means of the same column sharing the same letters are not significantly different ($p < 0.05$).

Table 12. Effects of cultivar, time of foliar spraying and plant growth regulators on yield and plant characteristics in analysis of combined experiments.

Cultivar	Time of foliar spraying	Plant growth regulators*									
		1	2	3	4	5	1	2	3	4	5
		No. of minitubers					Fresh weight of minituber (g)				
Agria	30 DAT	4.5^{ab}	8.3^{a}	5.1^{a}	4.7^{b}	4.1^{b}	47.9^{ab}	86.9^{a}	48.9^{ab}	29.2^{b}	33.3^{b}
	50 DAT	5.1^{a}	6.3^{a}	6.7^{a}	6.6^{a}	9.8^{a}	58.1^{a}	70.8^{b}	73.6^{a}	53.8^{a}	96.9^{a}
Savalan	30 DAT	4.0^{ab}	5.9^{a}	5.7^{a}	4.9^{b}	4.2^{b}	31.3^{bc}	50.8^{ab}	34.3^{b}	26.8^{b}	22.2^{b}
	50 DAT	3.6^{b}	7.2^{a}	5.6^{a}	6.9^{a}	4.6^{b}	25.7^{c}	62.2^{ab}	56.1^{ab}	64.9^{a}	36^{b}

Cultivar	Time of foliar spraying	Plant growth regulators*				
		1	2	3	4	5
		Dry weight of minituber (g)				
Agria	30 DAT	8.3^{a}	12.7^{a}	7.2^{ab}	5.4^{b}	3.9^{b}
	50 DAT	9.1^{a}	12.1^{a}	12.3^{a}	8.8^{a}	13.8^{a}
Savalan	30 DAT	4.7^{b}	4.7^{b}	6.01^{b}	4.2^{b}	3.6^{b}
	50 DAT	3.4^{b}	9.9^{a}	5.7^{b}	11^{a}	4.1^{b}

Means of the same column sharing the same letters are not significantly different ($p<0.05$).
*1= Control, 2= JA (5 mg/L), 3= JA (10 mg/L), 4= PBZ (50 mg/L), 5= PBZ (100 mg/L).

significant difference was observed in plant height when PBZ was used at 50 DAT in comparison with the control in both studied cultivars. In cultivar Agria, PBZ applied in 50 and 100 mgL^{-1} at 30 DAT significantly reduced plant height by about 53% in comparison with the control, whereas in cultivar Savalan only the use of 100 $mgL^{-1}$of PBZ significantly reduced plant height by about 55% compared to the control. As a result, the effect of PBZ on plant height depends on cultivar and time of foliar spraying. These findings were obtained in the aeroponic system in the present research, while the previous results had been observed in the *in vitro*, greenhouse, and field conditions.

This research showed that PBZ (50 and 100 mgL^{-1}) did not have a significant effect on the shoot growth reduction at 50 DAT, because the growth and development of the stem and leaves were completed at this time. In the present study, the use of 100 mgL^{-1} PBZ in cultivar Agria and 5 and 10 mgL^{-1} JA and also 50 mgL^{-1} PBZ in cultivar Savalan significantly produced the maximum number, fresh and dry weights of minitubers per plant at 50 DAT. But, at 30 DAT, the use of 5 mgL^{-1} JA increased significantly the number, fresh and dry weights of minitubers per plant, whereas the use of 100 mgL^{-1} PBZ significantly reduced dry weight of minitubers per plant in both tested cultivars. Tekalign and Hammes (2004) reported that dry matter accumulation and partitioning were influenced by PBZ treatment. PBZ treatment greatly increased the partitioning of assimilates to the tubers while reducing leaf, stem, root and stolon growth; thus, in tubers of treated plants, more starch grains were observed. This event resulted in an increase in tuber fresh mass and percentage of dry matter, while it reduced the number of tuber in the greenhouse conditions. In the present research, the positive effect of PBZ on the improvement of fresh and dry weight of minitubers in the aeroponic system was observed. Also, the results showed that the use of this plant growth regulator at 50 DAT increased the number of minitubers. Increased fresh and dry weight of potato tuber in response to PBZ treatment under greenhouse conditions was reported by Balamani and Poovaiah (1985). In our aeroponic system, the use of JA (5 mgL^{-1} JA at 30 DAT) in cultivar Agria increased the number and fresh weight of minitubers. The positive effect of exogenously applied jasmonate on tuber formation was also reported in soil cultivation system. An earlier tuber formation using a medium supplemented with JA was observed in yam. In this plant, after 7 days, 46% of the nodes produced a microtuber and length and weight of tubers were increased in response to JA treatment (Ondo Ovono *et al.,* 2010). Kim *et al.* (2005) reported that in greenhouse experiments, tuber weight was decreased by using 25 mgL^{-1} JA, whereas the concentration of 5 mgL^{-1} JA significantly increased the tuber weight in Chinese yam. In the present research, the use of JA (at 50 DAT) in cultivar Savalan also significantly increased the tuber weight of minitubers. Overall, this is the first report showing the positive effects of PBZ and JA on the number of potato minitubers produced in aeroponic cultivation system.

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