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Yield of Potato Minitubers under Aeroponics, Optimized for Nozzle Type and Spray Direction

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***Abstract*. Potato seed production by conventional methods represents a sizeable investment that, when passed on to farmers, can decrease their profit margins. Potato minitubers produced by aeroponic systems are space- and cost-efficient, and they also provide healthy propagules to be used by farmers. We evaluated the effects of different misting nozzle types, with and without an antidrip feature, and spray direction on potato minituber yield using the Federal University of Viçosa (UFV) Aeroponic System. Potato plants (cv. Agata) propagated from sprouts were grown in a covered, high-density 100-L polyethylene bucket. The experiment was set up in a randomized complete block design with four replicates and eight treatments combining misting nozzle types (Fogger, MA-30, and CoolNet) with and without antidrip and comparing upward with downward spray directions. Plants were evaluated weekly from 33 to 68 days after transplant (DAT). The parameters used to evaluate treatments were number and mass of minitubers as a function of harvest times, dry mass of roots, stems, leaves, and total biomass. The number and fresh weight of minitubers, as well as root dry weight, stems, leaves, and total biomass were affected by misting nozzle types and spray direction. Treatments also affected biomass partitioning of roots, stem biomass, and the shoot:root ratio. There was also an effect of harvest time on the number and fresh weight of minitubers for various combinations of misting nozzle type and spray direction, except for minituber number with the CoolNet misting nozzle without antidrip and downward spray direction. On the basis of the assessed parameters, the best minituber production system was achieved with the Fogger spray combined with no antidrip, a rate of 12 L·h^{-1}, and with the downward spray direction. The UFV Aeroponic System produced an average of 491 minitubers per plant. This system is simple to implement and may lead to a more affordable upscaling of potato seed minituber production.**

As new challenges in crop production emerge, the enhancement and improvement of production systems, including aeroponics, must be dynamic and continual. Among these challenges is the maximization of minituber multiplication rate at a reduced cost while maintaining plant health. The production of seed potatoes in aeroponic systems is an alternative to the basic seed potato production method.

In recent years, aeroponic systems were established to improve seed potato production (Buckseth et al., 2016; Mbiyu et al., 2018; Oraby et al., 2015; Rykaczewska, 2016; Silva Filho et al., 2018; Tessema et al., 2017; Tierno et al., 2014; Wang et al., 2017, 2018) and to maintain high production at a reduced cost (García, 2013). Aeroponic systems were proved to be more efficient and generally superior to other basic seed potato production systems because they have lower production costs, which makes implementation affordable (Chiipanthenga et al., 2012; Chindi et al., 2014; Corrêa et al., 2009; Factor et al., 2007; Lung'aho et al., 2010; Mateus-Rodríguez et al., 2013; Muthoni and Kabira, 2014; Otazú, 2010).

Current efforts to improve existing aeroponic systems aim to increase minituber multiplication rates. This can be partly accomplished by modifying several procedures and parameter, such as environmental conditions (Oraby et al., 2015), number of staggered harvests (Corrêa et al., 2009; Factor et al., 2007; Farran and Mingo-Castel, 2006; Singh et al., 2014), types of misting nozzles (Silva Filho et al., 2018), and spray direction. These factors, if explored, can lead to a greater multiplication of the virus-free genetic material (nuclear) in aphid-free environments (Oregon Seed Certification Service, 2018). Additionally, higher tuber yield reduces production costs, being advantageous not only to geneticists but also to commercial seed potato growers. The antidrip (or pressure-compensated) feature is used to prevent drip after irrigation is completed. However, when using antidrip nozzles, friction losses are increased, requiring pumps of greater power than the ones used without antidrip to provide the desired misting nozzle pressure.

The UFV Aeroponic System is a new system that could have been patented. However, we decided to make it available to the scientific community and, consequently, at no cost to commercial seed potato producers to give them free access to this technology. After the establishment of an aeroponic system developed and validated by the Federal University of Viçosa, Brazil (Silva Filho et al., 2018), further research was conducted to verify the possibility of adjusting certain features to improve the efficiency of that system. In this work, we evaluated different misting nozzles, with and without antidrip features, and with two spray directions on minituber potato yield in the UFV Aeroponic System. Treatments included the best performing treatments established previously (Silva Filho et al., 2018).

Materials and Methods

Site location and conditions

The experiment was conducted from April to July 2014 during two seasons: fall and winter at the Federal University of Viçosa (lat. 20°45′27.49″S, long. 42°52′11.01″W), 649 m above sea level, in a heated greenhouse with exhaust fans and evaporative cooling pads. The greenhouse had a 150-µm-thick low-density polyethylene cover (K50), which allowed 50% of ultraviolet light to shine on plants, with an antiaphid screen. Maximum and minimum temperatures and relative humidity during the study are shown in Fig. 1. Illumination was provided by natural daylight with ≈11 h of light per day.

Aeroponic system

The UFV Aeroponic System (Silva Filho et al., 2018) used a lidded high-density polyethylene container, with 100-L capacity and a lateral opening covered with a black plastic curtain (Fig. 2A). Irrigation was supplied by an electric water pump 1/2 hp (CP-4C/CP-4R; Dancor, Rio de Janeiro, RJ, Brazil) connected to a 1 1/4-inch (32-mm) PVC pipe with a 3/4-inch (20-mm) modular disk filter

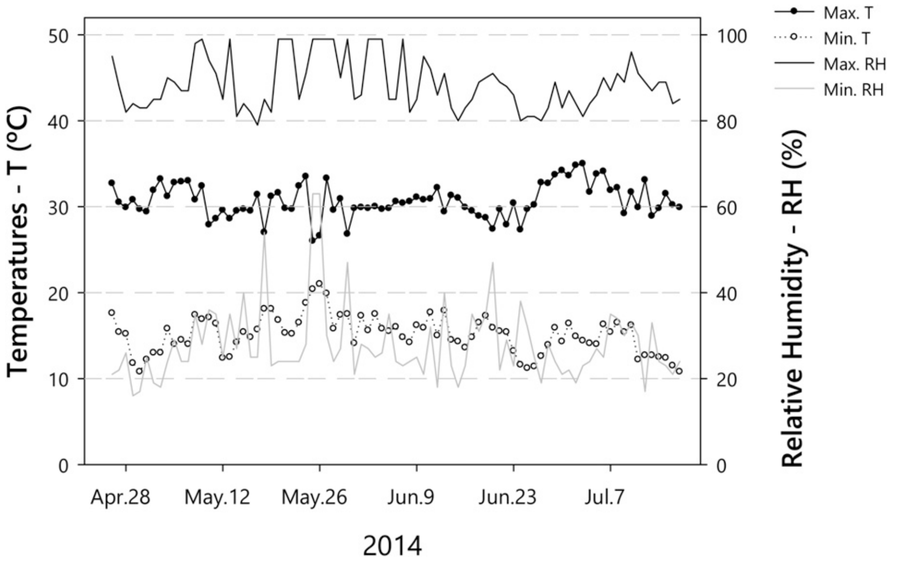

Fig. 1. Maximum and minimum temperatures and relative humidity inside the greenhouse used to grow the potato minitubers from April to July 2014.

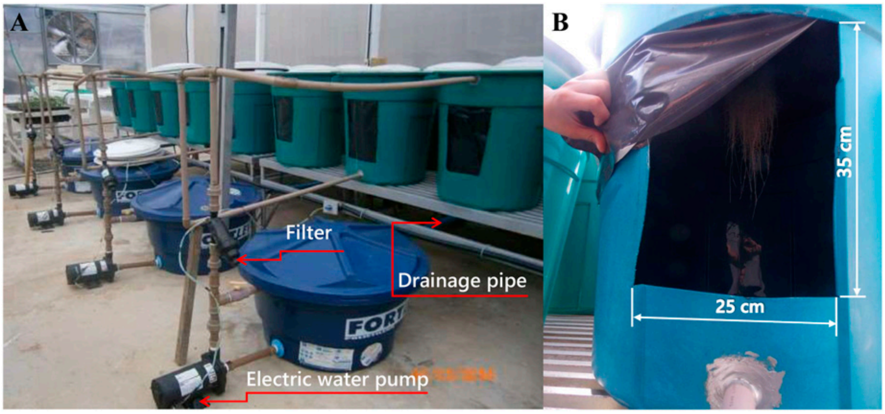

Fig. 2. UFV Aeroponic System details: whole system view shows the details of in-line filters (Filter), drainage pipe, and electric water pump (**A**). Side opening on the side of buckets used to grow minitubers allowed multiple harvests without disturbing the system (**B**).

of 120 mesh, one misting nozzle per bucket, and a nutrient solution return system provided by one drainage pipe per bucket (Fig. 2A). An opening of 25 × 35 cm on the side of each bucket allowed multiple harvests without disturbing the mist system (Fig. 2B). The flow of the nebulized nutrient solution was controlled by a programmed digital timer alternating between 20-s applications with 1-min intervals between each application.

Design

The experiment was set up in a randomized complete block design with four replicates and eight treatments combining a misting nozzle type Fogger, one nozzle per bucket, at a flow rate of 12 $L \cdot h^{-1}$, without antidrip, producing a droplet size of 69 µm at 3 atm (orange nozzle; NaanDanJain Irrigation Ltd., Israel) (Fig. 3A); MA-30, one nozzle per bucket, at a flow rate of 34 $L \cdot h^{-1}$, producing a droplet size of 100 µm at 3 atm (orange nozzle) (Fig. 3B); Agrojet (orange nozzle; Presidente Prudente, SP, Brazil) (Fig. 3C); and CoolNet Pro Fogger (a.k.a. CoolNet), one nozzle per bucket, at a flow rate of 7.5 $L \cdot h^{-1}$, producing a droplet size of 61 µm at 3 atm (white) manufactured by Netafim (Fresno, CA), with and without antidrip, and upward or downward spray direction (Fig. 3D, Table 1). The misting nozzles were installed in the center of the bucket at the bottom (upward spray direction) or at the top (downward spray direction). We conducted this study because there is no published work comparing misting nozzles in aeroponic systems. However, we did find work using an upward spray direction (Farran and Mingo-Castel, 2006; Ritter et al., 2001; Tsoka et al., 2012) or a downward spray direction (Otazú, 2010).

Propagation material

We bought minitubers from tissue culture plants (imported from Netherlands), with sizes of 20 to 30 mm. Potato plants (cv. Agata) were propagated by single sprouts detached from nuclear potato seed tubers. Initially, sprouts were planted in Deepot cells (Fig. 4A; 5.0 cm cell diameter × 17.8 cm cell depth; 262 mL, D16H, Stuewe & Sons, Inc., Tangent, OR) containing Tropstrato HT Hortaliças as the growth substrate (pine bark, peat, expanded vermiculite, enriched with macro and micronutrients, Viva Verde Company, Mogi Mirim, São Paulo, Brazil). Fifteen days after planting, 15-cm rooted sprouts were transferred with bare roots into a hole in the lid of the misting container (Fig. 4B). 'Agata' is a Dutch potato cultivar accounting for 55% of the potato produced in Brazil (Associação Brasileira da Batata, 2016).

Nutrient solution

Stock solutions of macro- and micronutrients were previously prepared and stored in 1-L amber-colored glass vials at a concentration of 2.0 M, except for KH_2PO_4 (1.0 M). For the first 21 DAT, seedlings were irrigated with the nutrient solution described in Table 2. This solution was previously shown to be effective for potato establishment (Furlani, 1998) and was composed of the following salts: KH_2PO_4; $MgSO_4.7H_2O$; $(NH_4)_2SO_4$; NH_4NO_3; $Ca(NO_3)_2.4H_2O$; KNO_3; $NaNO_3$; $CuSO_4$; $ZnSO_4.7H_2O$; $MnSO_4.H_2O$; H_3BO_3; $(NH_4)_6Mo_7O_{24}.4H_2O$; $FeCl_3.6H_2O$; and $C_{10}H_{14}N_2O_8Na_2.2H_2O$ (EDTA) providing macro- and micronutrients at concentrations specified in Table 2. A modified nutrient solution was prepared with dionized water 22 DAT to provide only macronutrients with the following salts: KH_2PO_4; $MgSO_4.7H_2O$; $(NH_4)_2SO_4$; NH_4NO_3; $Ca(NO_3)_2.4H_2O$; KNO_3; and KCl. The solution was balanced for cation and anions. Electrical conductivity measurements, pH monitoring, and nutrient solution replacement were done according to Silva Filho et al. (2018).

Data collection

Tuber production. Minituber production was evaluated by number (TUN) and fresh weight (TUF). Plants were evaluated weekly from 33 DAT to the end of the experiment (68 DAT). The minimum diameter of minitubers harvested ranged from 6 to 8 mm, and the maximum diameter ranged from 23 to 30 mm. After each harvest, the tubers were counted

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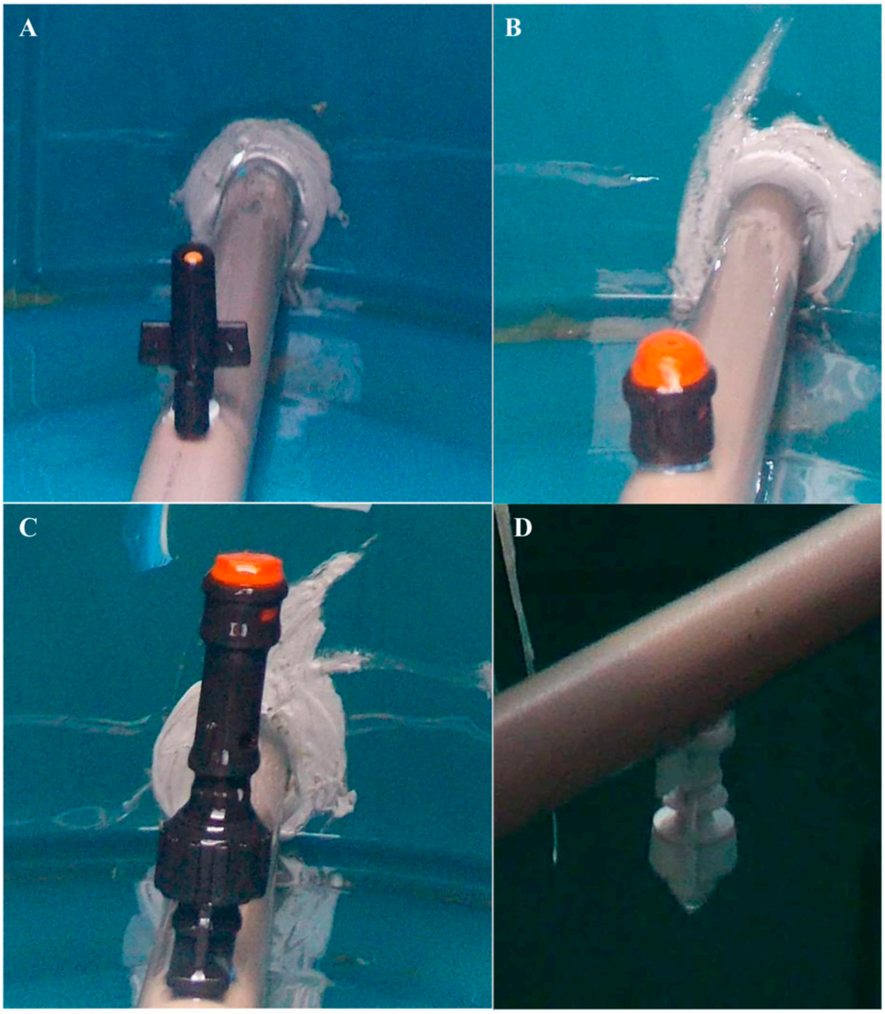

Fig. 3. Misting nozzles inside of buckets used to produce potato minitubers: Fogger (**A**), MA-30 without antidrip (**B**), MA-30 with antidrip (**C**), and CoolNet Pro Fogger without check valve (**D**).

Table 1. Treatments used to evaluate potato minitubers yield in the UFV Aeroponic System

Treatment	Misting nozzle[z]	Spray direction
1	Fogger without antidrip	Upward
2	Fogger without antidrip	Downward
3	MA-30 without antidrip	Upward
4	MA-30 without antidrip	Downward
5	MA-30 with antidrip	Upward
6	MA-30 with antidrip	Downward
7	CoolNet without check valve	Upward
8	CoolNet without check valve	Downward

[z] Flow rate ($L \cdot h^{-1}$) specified by the manufacturers were 12 for Fogger, 34 for MA-30, and 7.5 for CoolNet. UFV = Federal University of Viçosa.

Fig. 4. Seedling production in Deepot cells (**A**) and transplanting to lid holes on top of buckets (**B**).

and their weights recorded for each diameter range (6–8, 8–10, 10–16, 16–23, and 23–30 mm). The total sum of minitubers was calculated as the sum of all six harvests. For the production of seed potato minitubers, small sizes of 5 to 25 mm are usually accepted (Millam and Sharma, 2007, cited by Naik and Buckseth, 2018; Struik, 2007). Minitubers of smaller sizes can be easily transported for commercialization as seed propagules to be further multiplied in greenhouses (nuclear seed). Also, in describing the differences between minitubers and microtubers, Struik and Wiersema (1999), cited by Dimante and Gaile (2014), and Struik (2007) reported that minitubers can range from 5 to 25 mm in seed potato production systems, whereas Bado et al. (2016) mentioned microtubers ranging from 2 to 10 mm. We have found that sizes of ≈10 mm can be used for field propagation to upscale the yield of this virus-free material. However, sizes smaller than 10 mm (6–10 mm) are important for increasing the greenhouse multiplication rate and serve as propagules. Thus, based on the preceding diameters ranges, we harvested minitubers ranging from 6 to 30 mm diameter in our study.

Biomass production. At 68 DAT, when plants were at the early senescence stage, they were destructively harvested for dry matter of roots (RDM), stems (SDM), leaves (LDM), and total biomass (TODM). Plants were collected; separated into roots (stolons included), stems, and leaves; then placed in a forced-air circulation oven at 70 °C (158 °F) until constant mass was achieved. The total dry matter content was obtained by adding the dry matter content of roots (+ stolons), stems, and leaves.

Biomass partitioning. The amount of biomass allocated to the roots, stems, and leaves was calculated in relation to the total biomass produced, according to the formula: $BP_{organ} = \frac{DM_{organ}}{TODM}$. Additionally, the shoot:root ratio was calculated according to the formula: $SH : R_R = \frac{SHDM}{RDM}$, where BP_{organ} = biomass partitioned to the organ; DM_{organ} = dry matter of the organ; $TODM$ = total dry matter; $SH{:}R_R$ = shoot:root ratio; $SHDM$ = shoot dry matter; and RDM = root dry matter.

Data analysis. Data were used for analysis of variance and regression. Means were compared by the Tukey's test ($P < 0.05$). For comparison across all three harvest dates, the regression models were chosen based on biological logic. The significance of the regression coefficients was determined using the t test ($P < 0.10$) and the coefficient of determination $\left(R^2 = \frac{SS_{Regression}}{SS_{Treatment}}\right)$, where SS represents the sum of squares. Regardless of whether the interaction factor is significant, each variable was analyzed for its interactions, based on the interests of the study.

Results and Discussion

The antidrip (pressure compensation valve) is used to prevent changes in pressure during spraying. These differences in pressure may influence the droplet size and spray angle formed by misting nozzle. This will affect the cooling of the root zone and nutrient uptake. Antidrip nozzles are used in agricultural sprayers and mist cooling systems to optimize product application (insecticide, herbicide)—droplet size, spray angle, and avoiding wetting the floor, for example. When we chose antidrip misting nozzles, we thought that these benefits could improve the production of minitubers and decrease losses of nutrient solution. However, we found that, considering the high production of minitubers per plant achieved in our work, the use of antidrip nozzles in the UFV Aeroponic System is not necessary.

Table 2. Concentration of nutrients in two growing solutions used to produce potato minitubers in the UFV Aeroponic System.

	Concn of nutrients	
	Up to 21 DAT	22–68 DAT
Nutrients	($\text{mmol}\cdot\text{L}^{-1}$)	
Nitrate	12.43	9.88
Ammonium	1.26	1.36
Phosphorus	1.26	1.58
Potassium	4.68	5.85
Calcium	3.55	3.55
Magnesium	1.56	1.56
Sulfur	1.63	2.04
	($\mu\text{mol}\cdot\text{L}^{-1}$)	
Iron	35.84	35.84
Manganese	7.29	7.29
Boron	27.78	27.78
Zinc	0.92	0.92
Copper	0.31	0.31
Molybdenum	0.63	0.63

DAT = days after transplant.

The observed mean values of potato TUN and TUF at different harvest dates (DAT), the sum for the whole experimental period ($\sum$) as a function of misting nozzle combined with spray direction are shown in Table 3. The observed minituber productivity ($\sum$TUN and $\sum$TUF) was the highest in treatment 2, a combination of downward spray direction with the Fogger misting nozzle at 12 $\text{L}\cdot\text{h}^{-1}$, without antidrip (Table 3). All the treatments for potato minituber production with the UFV Aeroponic System were grown and harvested under nutrient solution, temperature, and relative humidity conditions described in Materials and Methods.

Each misting nozzle produces different sizes of water droplets; this is an important consideration because the smaller the droplets are, the higher is the total number of droplets suspended in to air. Additionally, smaller droplets cover a greater surface area. This may contribute to a higher uptake of nutrients by the roots (upward spray) or shoots (downward spray), possibly accounting for a higher production of minitubers (Buckseth et al., 2016; Clawson et al., 2000; Stoner, 1983). The Fogger misting nozzle at 12 $\text{L}\cdot\text{h}^{-1}$ without antidrip has a small droplet size (69 μm at 3 atm) and may have increased the relative humidity of the air. This increased humidity helped by providing a better environment in the root region and good conditions for plant growth and minituber development. The misting nozzle MA-30, at a flow rate of 34 $\text{L}\cdot\text{h}^{-1}$, produces a droplet size of 100 μm at 3 atm, whereas the CoolNet nozzle, at a flow rate of 7.5 $\text{L}\cdot\text{h}^{-1}$, produces a droplet size of 61 μm at 3 atm. The Fogger misting nozzle, at 12 $\text{L}\cdot\text{h}^{-1}$, without antidrip, produces a full conical jet, resulting in the highest performance of the three types of nozzles tested. The performance of this nozzle may have been superior to the others because of the fine mist generated around the root system environment, resulting in smaller droplet size together with the other benefits described.

The ideal droplet size for crops in an aeroponic system is between 30 and 100 μm. Droplet sizes larger than 100 μm tend to fall faster and generate less oxygen in the root zone environment (Gopinath et al., 2017; Morgan, 2005). Conversely, very small droplet sizes promote excessive growth of root hairs and may compromise the production of minitubers (Buckseth et al., 2016; Chiipanthenga et al., 2012; Gopinath et al., 2017; Lakhiar et al., 2018; Stoner and Clawson, 1998).

Table 3. Number (TUN) and fresh weight (TUF) of minitubers and harvest dates at 33, 40, 47, 54, 61, and 68 d after transplant (DAT) and total sum of minitubers ($\sum$) for the respective combinations of misting nozzle types and spray directions in the UFV Aeroponic System.

		Misting nozzle			
		Fogger w/o antidrip 12 $\text{L}\cdot\text{h}^{-1}$	MA-30 w/o antidrip 34 $\text{L}\cdot\text{h}^{-1}$	MA-30 w/antidrip 34 $\text{L}\cdot\text{h}^{-1}$	CoolNet w/o check valve 7.5 $\text{L}\cdot\text{h}^{-1}$
DAT	Spray direction	TUN (tubers/plant)			
33	Upward	12.50 aA	12.50 aA	17.75 aA	14.75 aA
	Downward	19.25 aA	22.75 aA	17.25 aA	13.25 aA
40	Upward	40.00 aA	16.75 bB	31.00 aAB	26.75 aAB
	Downward	47.00 aA	38.25 aA	38.75 aA	32.00 aA
47	Upward	62.25 bA	24.50 bB	37.00 bB	27.50 aB
	Downward	118.25 aA	44.50 aC	72.00 aB	40.00 aC
54	Upward	54.25 bA	26.00 aB	45.50 bA	24.25 aB
	Downward	104.25 aA	35.00 aC	78.75 aB	34.00 aC
61	Upward	48.50 bA	16.50 aB	24.75 bB	16.75 aB
	Downward	115.25 aA	14.50 aC	38.00 aB	8.50 aC
68	Upward	26.50 bA	15.75 aA	27.75 aA	12.50 aA
	Downward	86.75 aA	12.75 aC	34.75 aB	25.25 aBC
		TUF (g/plant)			
33	Upward	89.95 aB	119.26 bAB	113.02 aAB	164.58 aA
	Downward	51.92 aC	183.91 aA	110.69 aB	72.86 bBC
40	Upward	93.16 bAB	75.57 bB	130.09 bA	83.49 aAB
	Downward	197.52 aA	178.60 aA	219.95 aA	104.05 aB
47	Upward	143.63 bAB	90.79 bBC	186.44 bA	78.06 aC
	Downward	376.91 aA	139.34 aC	234.25 aB	91.46 aC
54	Upward	73.44 bA	27.92 aA	63.86 bA	25.09 aA
	Downward	214.45 aA	37.18 aC	110.54 aB	31.45 aC
61	Upward	44.29 bA	14.60 aA	29.46 aA	18.19 aA
	Downward	149.29 aA	16.49 aB	41.43 aB	10.55 aB
68	Upward	24.69 bA	13.99 aA	26.55 aA	13.75 aA
	Downward	87.35 aA	13.10 aB	32.37 aB	15.40 aB
		TUN (tubers/plant)			
$\sum$	Upward	244.00 bA	112.00 bB	183.75 bAB	122.50 aB
	Downward	491.00 aA	167.75 aC	279.50 aB	153.00 aC
		TUF (g/plant)			
$\sum$	Upward	469.14 bA	342.14 bA	549.42 bA	383.15 aA
	Downward	1077.42 aA	568.63 aB	749.22 aB	325.76 aC

Means followed by the same letter are not significantly different, lowercase letters compare the effect of spray direction, and uppercase letters compare the effect of misting nozzle type at each harvest date by Tukey's test ($P < 0.05$). w/ = with; w/o = without.

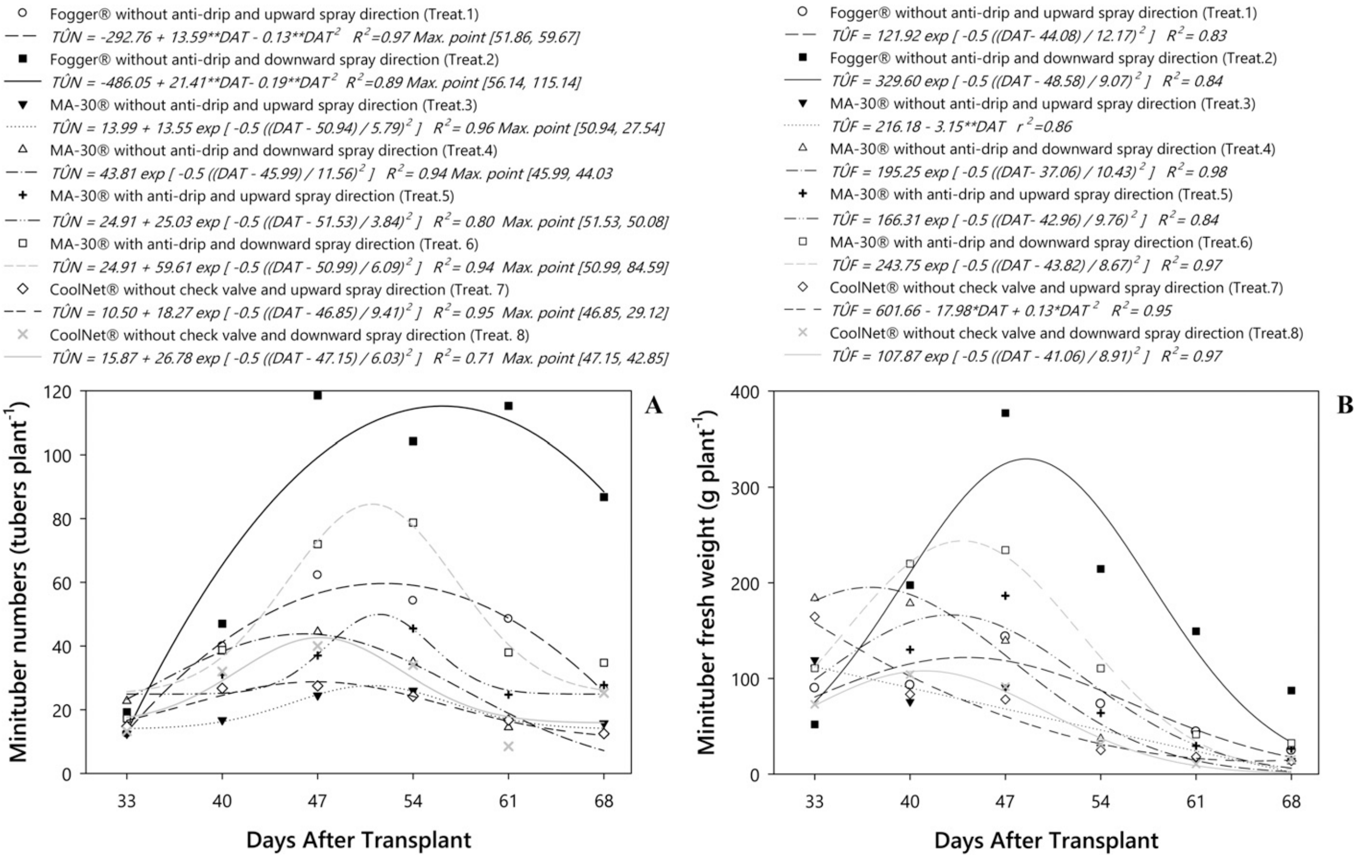

Fig. 5. Relationships between the production of minituber numbers (**A**) and fresh weight (**B**) with days after transplant (DAT) for the respective combinations of misting nozzle and spray directions. **, *Significant at $P = 0.01$ and 0.05, respectively, by *t* test.

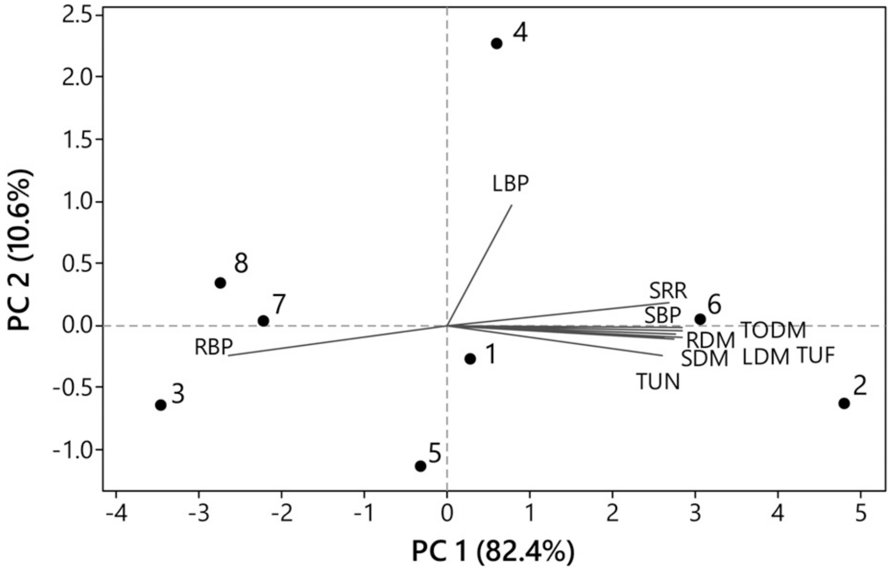

Fig. 6. Biplot of a principal component (PC) analysis on minituber potato yield experiment in the UFV Aeroponic System. Black circles: (**1**) Fogger without (w/o) antidrip and upward spray direction, (**2**) Fogger w/o antidrip and downward spray direction, (**3**) MA-30 w/o antidrip and upward spray direction, (**4**) MA-30 w/o antidrip and downward spray direction, (**5**) MA-30 with antidrip and upward spray direction, (**6**) MA-30 with antidrip and downward spray direction, (**7**) CoolNet w/o check valve and upward spray direction, and (**8**) CoolNet w/o check valve and downward spray direction. TUN = minituber numbers; TUF = minituber fresh weight; RDM = root dry matter; SDM = stem dry matter; LDM = leaf dry matter; TODM = total dry matter; RBP = root biomass partitioning; SBP = stem biomass partitioning; LBP = leaf biomass partitioning; SRR = shoot:root ratio.

Problems for optimization of aeroponics systems can arise due to the droplet size of the misting nozzle as well as the interval and duration time of the nutrient solution spray (Clawson et al., 2000).

A study to evaluate the effect of the available root zone volume on yield and quality characteristics of sweet basil cultivated aeroponically (Salachas et al., 2015) concluded that the increase of available oxygen in the spray of the nutrient solution in the roots increased the metabolism and the uptake of nutrients by plants, leading to better growth and development.

The average values for minituber numbers and fresh weight per plant were 491 and 1077 g, respectively. Prior works evaluating potato minituber production have found the following yields: 800 minitubers/m^2 (Farran and Mingo-Castel, 2006), 49 minitubers/plant, or 874 minitubers/m^2 (Factor et al., 2007), 84 minitubers/plant (Mateus-Rodríguez, 2010), 805 minitubers/m^2 larger than 20 mm (Abdullateef et al., 2012), 105 minitubers/plant or 2257 minitubers/m^2 (Cayambe et al., 2011), 64 minitubers/plant (Chang et al., 2011), 72 minitubers/plant (Mateus-Rodríguez et al., 2012), 36 minitubers/plant (Masengesho et al., 2012), 114 minitubers/plant (Oraby et al., 2015), and 171 minitubers/plant, or 475 minitubers/m^2 (Silva Filho et al., 2018). Most of the authors cited did not report cross diameter sizes, except Farran and Mingo-Castel (2006) (>20 mm), Abdullateef et al. (2012) (>20 mm), and

Table 4. Root (RDM), stem (SDM), leaf (LDM), and total (TODM) dry matter of potato minitubers for combinations of misting nozzle types and spray directions in the UFV Aeroponic System.

	Misting nozzle			
	Fogger w/o antidrip 12 L·h^{-1}	MA-30 w/o antidrip 34 L·h^{-1}	MA-30 w/antidrip 34 L·h^{-1}	CoolNet w/o check valve 7.5 L·h^{-1}
Spray direction	RDM (g/plant)			
Upward	3.79 bA	2.72 aA	3.04 bA	2.32 aA
Downward	5.67 aA	3.61 aAB	4.91 aA	1.94 aB
	SDM (g/plant)			
Upward	5.22 bA	1.82 aA	4.42 bA	2.47 aA
Downward	10.84 aA	4.93 aBC	8.46 aAB	1.80 aC
	LDM (g/plant)			
Upward	15.41 bA	7.86 aA	13.19 bA	8.68 aA
Downward	27.43 aA	16.27 aAB	23.32 aA	6.91 aB
	TODM (g/plant)			
Upward	24.41 bA	12.41 aA	20.65 bA	13.47 aA
Downward	43.94 aA	24.80 aBC	36.69 aAB	10.65 aC

Means followed by the same letter are not significantly different, lowercase letters compare the effect of spray direction, and uppercase letters compare the effect of misting nozzle type at each characteristic by Tukey's test ($P < 0.05$). w/ = with; w/o = without.

Table 5. Biomass partitioning of root (RBP), stem (SBP), and leaf (LBP) and shoot:root ratio (SRR) of potato minituber yield for combinations of misting nozzle types and spray directions in the UFV Aeroponic System.

	Spray direction	
	Upward	Downward
Misting Nozzle	RBP (g·g^{-1})	
Fogger w/o antidrip 12 L·h^{-1}	0.16 bA	0.13 bA
MA-30 w/o antidrip 34 L·h^{-1}	0.22 aA	0.14 abB
MA-30 w/antidrip 34 L·h^{-1}	0.16 bA	0.13 bA
CoolNet w/o antidrip 7.5 L·h^{-1}	0.19 abA	0.19 aA
	SBP (g·g^{-1})	
Fogger w/o antidrip 12 L·h^{-1}	0.21 aA	0.23 aA
MA-30 w/o antidrip 34 L·h^{-1}	0.15 bB	0.20 abA
MA-30 w/antidrip 34 L·h^{-1}	0.22 aA	0.23 aA
CoolNet w/o antidrip 7.5 L·h^{-1}	0.18a bA	0.17 bA
	LBP (g·g^{-1})	
Fogger w/o antidrip 12 L·h^{-1}	0.63 aA	0.64 aA
MA-30 w/o antidrip 34 L·h^{-1}	0.63 aA	0.66 aA
MA-30 w/antidrip 34 L·h^{-1}	0.62 aA	0.64 aA
CoolNet w/o antidrip 7.5 L·h^{-1}	0.63 aA	0.64 aA
	SRR (g·g^{-1})	
Fogger w/o antidrip 12 L·h^{-1}	5.45 aA	6.56 aA
MA-30 w/o antidrip 34 L·h^{-1}	3.55 bB	5.99 abA
MA-30 w/antidrip 34 L·h^{-1}	5.52 aA	6.83 aA
CoolNet w/o antidrip 7.5 L·h^{-1}	4.81 abA	4.42 bA

Means followed by the same letter are not significantly different, lowercase letters compare the effect of misting nozzle type, and uppercase letters compare the effect of spray direction at each characteristic by Tukey's test ($P < 0.05$). w/ = with; w/o = without.

Masengesho et al. (2012) (>25 mm). Those minituber yields (minitubers/plant) previously reported were smaller than those obtained in our study, although the sizes of the minitubers were not compared. In the most effective treatment (T2), plants produced an average of 491 minitubers/plant using the Fogger misting nozzle at 12 L·h^{-1} and a downward spray. Such minituber productivity, at 2.78 plants/m^2, corresponds to 1364 minitubers/m^2. We did not evaluate the quality of minitubers regarding the minitubers production of plants generated from small, medium, or large minitubers in the range of 6- to 30-mm cross diameter. However, this is a valid point that should be evaluated in future research studies. In a similar line of thought, Radouani and Lauer (2015) reported that cultivar Nicola was not influenced by type nor size of tubers, whereas cultivar Russet Burbank was sensitive to tuber sizes.

Relationships between the production of TUN and harvest times (DAT) for each combination of misting nozzle and spray direction are presented (Fig. 3A). In each statistically significant treatment, 1, 2, 4, 6, and 7, the maximum of the sum of minituber number values ($\sum$TUN) occurred with a staggered harvest performed at 52, 57, 46, 52, and 47 DAT, respectively (Fig. 5A) and reached the estimated value of 60, 118, 41, 69, and 26 minitubers/plant in each harvest date, respectively. That means the maximum $\sum$TUN adjusted values occurred around the fourth harvest. Under other experimental and environmental conditions, Abdullateef et al. (2012) found the highest minituber numbers in the fourth harvest, at 87 DAT; Factor et al. (2007) reported increases in minituber numbers up to 74 DAT.

Statistically significant relationships between the production of TUF and harvest times (DAT), for the respective combinations of misting nozzle and spray directions, are presented in Fig. 5B. In each statistically significant treatment, 1–7, the total of fresh weight values occurred at an earlier stage than the total of minituber numbers (Figs. 6A and B). Tuberization is a complex process because it involves factors such as genetics, hormones, enzymes, nutrients, photoassimilate partitioning, temperature, day length, and solar radiation (Dutt et al., 2017). The lower third of the below-ground stem produced larger tubers than the higher parts of the stem (Pavek and Thornton, 2009; cited by Wohleb et al., 2014; Plaisted, 1957). Possibly, this earlier production of fresh weight relative to the number of minitubers can be accounted by the fact that these minitubers originated from the bottom third of the stem.

The average values of RDM, SDM, LDM, and TODM at the end of the experiment, as function of the combinations of misting nozzle and spray direction, are presented in Table 4. When the spray direction was upward, none of the measured characteristics were affected by misting nozzle types (Table 4). With the Fogger misting nozzle (T1 and T2) and MA-30 with antidrip (T5 and T6), downward spray direction resulted in higher RDM, SDM, LDM, and TODM values than MA-30 without antidrip (T3 and T4) or CoolNet (T7 and T8). Downward spray with the Fogger misting nozzle (T2) resulted in higher TUN and TUF than MA-30 with antidrip (T6), as shown in Table 3. Spray direction significantly affected biomass production. When the spray direction was downward, it seemed that there was more fog accumulation in the root zone and for a longer time. This may lead to higher nutrient uptake, photoassimilate production, and consequently higher biomass production.

The ideal type of misting nozzle for aeroponics depends on several factors, among them plant species, the aeroponic system, and spray direction. The type of misting nozzle may influence seed potato productivity through changes in droplet size, which can form different types of mists in the root growth environment and may interfere with water and nutrient absorption. For example, when using Fogger without antidrip misting (Treatment 2) we had a significantly ($P < 0.05$)

Table 6. Minituber numbers yield (tubers/plant) at 33, 40, 47, 54, 61, and 68 d after transplant (DAT) and total sum (∑) of minitubers for the respective combinations of cross diameter (Ø), spray directions, and misting nozzle types in the UFV Aeroponic System.

	Upward spray direction				Downward spray direction			
Ø (mm)	Fogger w/o antidrip 12 $L{\cdot}h^{-1}$	MA-30 w/o antidrip 34 $L{\cdot}h^{-1}$	MA-30 w/antidrip 34 $L{\cdot}h^{-1}$	CoolNet w/o antidrip 7.5 $L{\cdot}h^{-1}$	Fogger w/o antidrip 12 $L{\cdot}h^{-1}$	MA-30 w/o antidrip 34 $L{\cdot}h^{-1}$	MA-30 w/antidrip 34 $L{\cdot}h^{-1}$	CoolNet w/o antidrip 7.5 $L{\cdot}h^{-1}$
33 DAT								
23–30	5.75 aA	5.00 abA	6.00 aA	7.50 aA	2.50 bB	7.75 bA	3.75 bAB	2.75 abB
16–23	6.00 aA	6.25 aA	5.75 abA	5.50 abA	7.50 aB	13.25 aA	9.75 aAB	6.25 aB
10–16	0.75 bA	1.25 bcA	4.25 abA	1.25 bcA	8.25 aA	1.50 cB	3.25 bB	3.25 abB
8–10	0.00 bA	0.00 cA	1.50 bcA	0.25 cA	0.75 bA	0.25 cA	0.25 bA	0.25 bA
6–8	0.00 bA	0.00 cA	0.25 cA	0.25 cA	0.25 bA	0.00 cA	0.25 bA	0.50 bA
40 DAT								
23–30	3.50 bA	3.25 abA	4.00 bA	3.25 bA	10.50 bA	6.50bcA	10.50 aA	3.25 bA
16–23	6.50 bA	3.50 abA	7.00 bA	6.25 abA	11.75 bA	12.00a bA	13.50 aA	12.00 aA
10–16	17.00 aA	8.75 aB	17.00 aA	13.25 aAB	22.00 aA	17.00 aAB	13.00 aB	13.75 aB
8–10	5.50 bA	1.25 abA	1.75 bA	2.75 bA	1.75 cA	1.75 cA	1.25 bA	3.00 bA
6–8	7.50 bA	0.00 bA	1.25 bA	1.25 bA	1.00 cA	1.00 cA	0.50 bA	0.00 bA
47 DAT								
23–30	1.50 cA	0.50 bA	3.00 bA	0.50 bA	8.50 cdA	1.00 cA	4.00 bA	0.25 bA
16–23	5.75 bcA	5.50 abA	9.00 abA	4.50 bA	26.75 bA	13.75 abB	13.75 bB	2.75 bC
10–16	27.50 aA	15.75 aB	19.75 aAB	17.75 aAB	59.75 aA	21.00 aC	38.75 aB	26.00 aC
8–10	15.25 bA	2.50 bB	4.50 bAB	3.75 bB	18.00 bcA	8.50 bcA	8.50 bA	10.00 bA
6–8	12.25 bcA	0.25 bB	0.75 bB	1.00 bB	5.50 dA	0.25 cA	7.00 bA	1.00 bA
54 DAT								
23–30	1.25 cA	0.00 bA	0.00 cA	0.00 aA	3.50 cA	0.50 bA	1.75 dA	0.00 bA
16–23	3.75 bcA	1.00 abA	2.25 bcA	0.75 aA	18.25 bA	2.00 bB	6.00 cdB	0.75 bB
10–16	25.25 aA	12.25 aB	26.25 aA	11.50 aB	52.25 aA	19.25 aC	38.75 aB	10.00 abC
8–10	13.75 abA	8.75 abA	13.00 bA	5.25 aA	20.75 bA	8.25 abB	18.00 bAB	14.00 aAB
6–8	10.25 bcA	4.00 abA	4.00 bcA	6.75 aA	9.50 bcA	5.00 bA	14.25 bcA	9.25 abA
61 DAT								
23–30	0.25 dA	0.00 aA	0.00 bA	0.00 aA	0.00 dA	0.00 aA	0.00 cA	0.00 aA
16–23	1.25 cdA	0.00 aA	1.00 bA	0.25 aA	9.00 cA	1.00 aAB	1.50 cAB	0.00 aB
10–16	15.75 abA	8.00 aA	14.00 aA	8.25 aA	69.25 aA	6.75 aC	19.25 aB	3.25 aC
8–10	21.50 aA	5.50 aB	7.75 abB	4.50 aB	27.50 bA	2.25 aC	11.00 abB	2.75 aBC
6–8	9.75 bcA	3.00 aA	2.00 bA	3.75 aA	9.50 cA	4.50 aA	6.25 bcA	2.50 aA
68 DAT								
23–30	0.00 bA	0.00 aA	0.00 bA	0.00 aA	0.00 cA	0.00 aA	0.00 cA	0.00 bA
16–23	0.75 bA	0.00 aA	0.50 bA	1.00 aA	7.00 cA	0.50 aA	0.75 bcA	0.00 bA
10–16	10.00 aAB	7.75 aAB	13.00 aA	4.00 aB	31.50 aA	5.75 aC	13.50 aB	2.00 bC
8–10	5.00 abA	2.75 aA	8.75 aA	3.50 aA	21.75 bA	2.00 aC	8.25 abBC	10.50 aB
6–8	10.75 aA	5.25 aA	5.50 abA	4.00 aA	26.50 abA	4.50 aC	12.25 aB	12.75 aB
Harvest ∑								
23–30	12.25 dA	8.75 bA	13.00 bA	11.25 bA	25.00 dA	15.75 bA	20.00 bA	6.25 cA
16–23	24.00 cdA	16.25 bA	25.50 bA	18.25 bA	80.25 bcA	42.50 abB	45.25 bB	21.75 bcB
10–16	96.25 aA	53.75 aB	94.25 aA	56.00 aB	243.00 aA	71.25 aC	126.50 aB	58.50 aC
8–10	61.00 bA	20.75 abB	37.25 bAB	20.00 bB	90.50 bA	23.00 bB	47.25 bB	40.50 abB
6–8	50.50 bcA	12.50 bB	13.75 bB	17.00 bB	52.25 cdA	15.25 bB	40.50 bAB	26.00 abcAB

Means followed by the same letter are not significantly different, lowercase letters indicate effect of cross diameter, and uppercase letters indicate effect of misting nozzle type at each harvest date by Tukey's test ($P < 0.05$). w/ = with; w/o = without.

higher production of minitubers compared with the other misting nozzles used (Table 3, Fig. 5A). Each type of misting nozzle with different opening angles produces differing distribution profiles of nutrient solution, which can influence tuber yield (Vilela, 2002). Although the angles for each nozzle misting were not measured, we noticed that the CoolNet misting nozzle had a larger spray angle, and this probably hampered its better performance in minituber production. Additionally, systems that work with a high-pressure spray are at a greater risk of clogging the nozzles. Furthermore, a larger volume of nutrient solution provides a more efficient cooling of the root environment (Zolnier, 2001).

Regardless of the time delay between transfer to aeroponic system and the maximal minituber production, the number and timing of harvests are key factors affecting minituber production. To fully optimize any aeroponic system, it is necessary to consider many factors such as the composition of the nutrient solution, plant density, harvest intervals, and possible interactions between them (Farran and Mingo-Castel, 2006; cited by Chindi et al., 2014). Future work could further improve the UFV Aeroponic System using these recommended parameters and their interactions. Our harvesting schedule was based on reports from several staggered harvests that have led to an increase in the production of minitubers (Corrêa et al., 2009; Factor et al., 2007). In a study that evaluated the productivity of cv. Kufri Bahar under four harvest intervals (3, 7, 10, and 14 d between harvests), in an aeroponic system, Singh et al. (2014) found increased production as harvest interval decreased and suggested that harvesting at 3-d intervals resulted in maximum number of minitubers per plant.

In our work, the misting nozzle types affected the root and stem biomass partitioning, as well as shoot:root ratio for both spray directions. There was a greater allocation of root biomass with MA-30 without antidrip compared with the Fogger without antidrip and MA-30 with antidrip. The opposite was observed for the allocation of stem biomass and shoot:root ratio, where there was less allocation of stem biomass with MA-30 without antidrip compared with the Fogger without antidrip and MA-30 with antidrip for upward spray direction. For downward spray direction, there was a greater allocation of root biomass with CoolNet without antidrip compared with the MA-30 with antidrip and Fogger without antidrip. The opposite occurred with respect to stem biomass partitioning and shoot:root ratio. There was less stem allocation when using CoolNet without antidrip compared with the MA-30 with antidrip and Fogger without antidrip (Table 5). The mean values obtained in our work corroborate those of Silva Filho et al. (2018), which studied combinations of misting nozzle types and the coating on the bucket's inner wall on the yield of basic potato seed minitubers. They reported mean values for root and stem biomass partitioning of 0.22 and 0.17 with misting nozzle MA-30 with antidrip and 0.25 and 0.25 with misting nozzle MA-30 without antidrip, without polyurethane in the inner lining of the bucket, respectively. In our study, there were no effects of either misting nozzle types or spray directions for leaf biomass partitioning (Table 5).

The spray directions affected the root and stem biomass partitioning and shoot:root ratio only in the treatment MA-30 without antidrip. There was a greater allocation of root biomass with an upward spray direction, whereas the opposite was observed with stem biomass allocation and shoot:root ratio: there were greater shoot:root ratios and allocation of stem biomass using a downward spray direction (Table 5). The mean values reported for shoot:root ratios in the present study were higher than those of Silva Filho et al. (2018). These results of biomass partitioning suggest that the higher the biomass allocation in the roots (roots + stolons), the lower the production of minitubers per plant (Tables 3 and 5). It is possible that the plant is directing photoassimilates to increase the root system and thereby improve the uptake of nutrients and water (Feller et al., 2015) due to the low efficiency of the misting nozzle. According to Irving (2015), under low availability of water, the allocation of carbon in the roots can increase to the detriment of the allocation of carbon in the shoot with the functional objective of maximizing water absorption. However, the physiological mechanism underlying this phenomenon is still unknown.

The two dimensions of the principal component analysis (PCA) can explain 93% of the original variability of this work (Fig. 6). The shoot:root ratio; LDM, TODM, RDM, and SDM; stem biomass partitioning; fresh weight; and number of minitubers are the most important parameters to differentiate treatments. Additionally, the PCA shows that the Fogger misting nozzle without antidrip and downward spray direction (T2) had the greatest LDM, TODM, RDM, and SDM; stem biomass allocation; and minituber number and fresh weight, confirming the results of Tables 3–5. The treatments with MA-30 without antidrip and upward spray direction (T3) and MA-30 with antidrip and upward spray direction (T5) have a higher root biomass allocation. The treatments (Fig. 6) with MA-30 without antidrip and downward spray direction (T4) and MA-30 with antidrip and downward spray direction (T6) resulted in the highest leaf biomass allocation and shoot:root ratio.

Table 6 shows the number of minitubers yielded, according to cross diameter, spray direction, and misting nozzle type. The misting nozzle Fogger was significantly better than the other misting nozzles with regard to producing minitubers of cross diameter ranging from 6 to 23 mm, using the downward spray direction. Regardless of spray direction and misting nozzle type, the best minituber yield was obtained with cross diameter ranging from 10 to 16 mm (Table 6). In our methodology section, it was established that minitubers with a minimum of 6- to 8-mm cross diameter could be used for propagation. Future work with this aeroponic system can establish, according to target size and function, a new harvesting standard of cross diameter for minitubers.

The possible benefits of this system include higher cooling of the root zone, stimulating nutrient uptake, plant growth, and high production of minitubers.

Conclusions

The treatment with the Fogger misting nozzle without antidrip at a flow rate of 12 $L \cdot h^{-1}$ at 3 atm and downward spray direction resulted in a potato minituber yield significantly higher (221%) than the least effective treatment. This treatment (Fogger) also resulted in a potato minituber yield significantly higher (76%) than the second best treatment: MA-30 misting nozzle with antidrip at a flow rate of 34 $L \cdot h^{-1}$ at 3 atm and downward spray direction. Thus, the UFV Aeroponic System was validated and provided optimal yield of potato mintuber with the Fogger misting nozzle, according to specifications described here. However, the antidrip feature adds to the friction losses, and we are not sure it provides any benefit to the grower. This seed minituber production system is affordable and practical and can be used by any producer of potato seeds.

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