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Comparison of aeroponics technology with a conventional system of production of potato minitubers in the conditions of the Czech Republic

Milan Čížek, Zuzana Komárková*

Potato Research Institute Havlíčkův Brod, Ltd., Havlíčkův Brod, Czech Republic
**Corresponding author: cizek@vubhb.cz*

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Abstract: Aeroponics would appear to have a number of potential attributes to make potato production more efficient. In a 3-year experiment, from 2019 to 2021, potatoes were grown in aeroponic units using two nutrient solutions as well as in a conventional polycarbonate greenhouse in a substrate. Potato cultivars Adéla, Zuza and Ornella were used in all experiment years. No statistically significant effect of nutrient solution or potato cultivar on the number and weight of tubers was found in the trial. However, the advantages of aeroponics over conventional technology were statistically proven. The number of tubers per plant in aeroponic units ranged from 2.4 (2019, cv. Adéla) to 41.0 (2021, cv. Zuza), while in the greenhouse, they ranged from 3.9 (2019, cv. Adéla) up to 12.6 (2021, cv. Adéla). The average weight of tubers in aeroponic units ranged between 2.0 g and 9.9 g per plant (2 to 10 successive harvests), and in the greenhouse, 22.7 g to 41.9 g per plant (single harvest). The influence of cultivar on the average weight of tubers within individual cultivation technology variants was statistically proven only for polycarbonate greenhouse: only one harvest after the end vegetation.

Keywords: *Solanum tuberosum* L.; soilless technology; nutrition; planting density; tissue culture

Aeroponics is one of the plant cultivation technologies which do not use any substrate. The earliest reports of aeroponics date back to the 1940s and 1950s. Research on this technology was initially focused on citruses, avocado, apple and tomato (Stoner 1983). In the 1990s, several attempts were made in South Korea to adapt it for growing potatoes (Kang et al. 1996, Kim et al. 1997, Chang et al. 2012). Since then, there have been many studies on the use of aeroponics for potato production.

Aeroponics is an alternative technology for producing mini-tubers during seed potato propagation (Rykaczewska 2016). It is a method of cultivating plants without the use of a solid or liquid medium. In the case of potatoes, it is used mainly in the new breeding and propagation of seed potatoes. The production of potato mini-tubers through aeroponics is practised all over the world. In Asia, Europe and Latin America, it also serves for research purposes and commercial seed potato production (Mateus-Rodriguez et al. 2013). The reason is the effort to minimise the number of field propagation cycles due to its low efficiency and the risk of infecting the seed by disease agents (Chiipanthenga et al. 2013). Aeroponic technology has the potential to improve production and reduce costs compared to conventional or other soil-free methods, namely hydroponics (growing in nutrient solutions). Aeroponics effectively uses the vertical space of the greenhouse and air humidity to optimise the development of roots, tubers and stems (Otazú 2010). Aeroponic technology has a high multiplication ratio of 1:50–100 (Lung'ago et al. 2010) compared to conventional *in vitro* plants (1:5–6). Farran and Mingo-Castel (2006) adjusted this

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value to 1:13 (e.g., 800 mini-tubers/m^2 at a density of 60 plants/m^2 during a five-month growing cycle with successive weekly harvesting).

Aeroponics supplies the plants through an aerosolised nutrient solution, which is sprayed at regular intervals into the root zone. The roots are constantly in contact with fresh air, which leads to intensive respiration of root tissues and accelerated metabolism. The result is intensive biomass production in both root and shoot systems, including mini-tubers (Otazú 2010, Andrade-Piedra et al. 2019). Using aeroponic technology, it is possible to achieve a yield of 30 to 40 mini-tubers per potato plant. The aeroponic system has the advantage that the tubers can be harvested when they are the right size, thus improving the production of mini-tubers (Ritter et al. 2001). The potato propagation system in aeroponics technology has the potential to eliminate up to one generation of seed potato propagation in the field, thus reducing costs and increasing the quality of plant health in the first generation of field production (Nichols 2005). Aeroponics allows a large production of relatively uniform potato mini-tubers at the same time. The key to tuber production in aeroponics is the control over tuber initiation (Christie and Nichols 2004). The CIP (International Potato Center, Lima, Peru) promotes the production of potato mini-tubers using an aeroponics system in the Andean highlands and in some African countries (Otazú et al. 2010, Andrade-Piedra et al. 2019).

This study aimed to evaluate the use of aeroponic technology for the production of potato mini-tubers in the years 2019 to 2021 compared with a classic substrate technology in the conditions of the Czech Republic.

MATERIAL AND METHODS

Plant materials and *in vitro* propagation. The starting plant material for potatoes was tissue culture plants (*in vitro* cultures). In the experiment, the starting plant materials of three potato cultivars bred in the Bohemian-Moravian Highlands in the Czech Republic were used: Adéla (early, R), Zuza (semi-early, PR) and Ornella (semi-late, PP). Early, semi-early and semi-late potato cultivars are most often grown in the Czech Republic, so they were selected for the experiment.

Tissue culture plants were obtained by *in vitro* nodal cutting and cultivation on Muraschige-Skoog nutrient medium supplemented with 2% sucrose and 0.7% agar. The plants were cultivated at a photoperiod of 16 h with 8 h of darkness at 20 °C and under illumination intensity of 3 500 lux. Tissue culture plants were planted in perlite, and after sufficient rooting, the plants were transplanted into two aeroponic units and a polycarbonate isolation greenhouse unit (PG, 21–26 days after planting).

Aeroponic seedlings. Tissue culture plants were planted in the aeroponic units (AU) and the polycarbonate isolation unit (hereinafter PG) with the spacing of 0.25 × 0.25 m, i.e. the plant density was 25/m^2 (21 to 26 days after planting). According to Çalışkan et al. (2021), this plant density is optimal for the highest production of potato mini-tubers. The average daily temperature inside the greenhouse ranged from 17–27 °C, and relative humidity ranged between 64–68%.

Site description and aeroponic system. In the years 2019–2021, experiments took place at the Potato Research Institute in Havlíčkův Brod, in the Bohemian-Moravian Highlands in the Czech Republic (49°36'28''N, 15°34'51''E, 422 m a.s.l.). Aeroponic units were installed inside of a classic greenhouse that was equipped with natural gas heating and internal water distribution. The aeroponic units were separated from the rest of the greenhouse by an access chamber. The units were tunnels made by a metal frame with outer walls made from extruded polystyrene sheets. On the ceiling of the inner root space, there were hoses with nozzles to distribute the nutrient solutions to the plant roots. The nutrient solutions in storage tanks were cooled. The spraying system was controlled by an automatic control valve with a timer.

In all experimental years, a commercial special nutrient solution intended for aeroponics (solution 1, General Hydroponics) was applied to potatoes, which was combined with fertilisers with different ratios of N, P, K, supplemented with Mg, Ca, S and micronutrients. For comparison, the second nutrient solution was prepared according to Otazú (2010) (solution 2, composition: N 0.16 g/L, P 0.15 g/L, K 0.27 g/L, Ca 0.15 g/L, Mg 0.10 g/L, S 0.19 g/L, Fe 0.009 g/L (EDTA), supplemented with micronutrients from commercial nutrient solution Bionova Micromix (B – water soluble; Cu – EDTA chelated; Fe – DTPA chelated; Mn – EDTA chelated; Mo – water soluble and Zn – EDTA chelated). The spraying time was 2 min with a 3 min pause; in 2021, it was 3 min with 8 min pause. The dosage was varied during the growing season depending on the developmental stage of the plants and the level of conductivity. The

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conductivity was adjusted from 0.9 mS/cm at the beginning of the experiment to 2.0 mS/cm at the end of the experiment. The pH value was adjusted to values between 5.5 and 6.5 during the vegetation cycle. Water from a deep well was used to prepare the nutrient solution and to replenish the water in the tanks. The water had an electric conductivity of 0.597 mS/cm, and the pH was around 6.2. According to Otazú (2010), water with a conductivity of up to 1.0 mS/cm is suitable for aeroponics.

The method of growing potatoes in aeroponic units was compared with the conventional method of growing in a substrate in a polycarbonate isolation unit (PG). In the PG variant, the plants were watered daily by an automated system, and sensors were placed under the ceiling to measure the temperature and humidity inside the polycarbonate units. Potatoes were planted and harvested by hand.

Experimental design and monitored variables. The plants were placed in two aeroponic units (AU1 and AU2); each aeroponic unit was fed a different nutrient solution (AU1 – solution 1; AU2 – solution 2). Substrate technology was used in PG, which was considered as the control variant for the experiment. In PG, the same number of plants was planted as in AUs. Plants of the Adéla, Ornella and Zuza cultivars were planted in each AU and PG. In the aeroponic units, tubers weighing more than 1 g (size 1–3 cm) were harvested at regular weekly intervals until the point of excess plant senescence; only one harvest took place in the polycarbonate unit from which the number and weight of tubers were evaluated.

All data were analysed using TIBCO Statistica 14.0 data analysis software (TIBCO Software Inc., Palo Alto, USA). The data collected were subjected to analysis of variance (ANOVA), and Tukey's multiple range tests were used to separate significantly different means at a significance level of $P \leq 0.05$ or $P \leq 0.01$.

RESULTS AND DISCUSSION

The number of tubers. 2019: More tubers were harvested from all cultivars in AU1 (average number of tubers per plant in cv. Adéla was 5.3, in cv. Ornella 4.2 and cv. Zuza 7.2) compared to AU2 (average number of tubers per plant in cv. Adéla was 2.4, in cv. Ornella 2.5 and cv. Zuza 3.9) (Table 1). The number of harvests ranged from two to four (Figure 1A). Although the number of tubers was higher in AU1, there was a statistically significant difference only for the cvs. Adéla and Zuza ($P \leq 0.01$). Compared to potatoes grown in the substrate in PG, more tubers per plant were formed only in the cvs. Adéla and Zuza in AU1. In PG, most tubers formed in the cv. Ornella (average of 10.6 tubers per plant), in the cv. Zuza, the average number of tubers per plant was 5.8. The fewest tubers formed in the cv. Adéla (average number per plant was 3.9).

2020: Significantly more tubers were harvested in both aeroponic units compared to PG ($P \leq 0.01$). In PG, the average number of tubers per plant ranged from 4.3 in the cv. Ornella to 8.5 in cv. Zuza (Table 1). In aeroponic units, the average number of tubers per plant ranged from 14.4 for the cv. Ornella in AU2 to 19.5 in cv. Ornella in AU1. In the cvs. Zuza and Adéla, more tubers were formed in AU2 (for cv. Adéla 14.6 tubers per plant in AU1 *vs.* 19.2 in AU2; for cv. Zuza 17.6 pcs per plant in AU1 *vs.* 18.5 in AU2). However, the differences were not statistically significant. On the contrary, the difference in the cv. Ornella between

Table 1. The effect of nutrient solutions and cultivation technology on the number of tubers in potato cultivars

Cultivation technology	cv. Adéla			cv. Ornella			cv. Zuza		
	2019	2020	2021	2019	2020	2021	2019	2020	2021
The average number of tubers per plant (–)									
AU1	5.3	14.7	34.0	4.2	19.5	25.6	7.2	17.7	41.0
AU2	2.4	19.2	33.7	2.5	14.4	30.7	3.9	18.5	36.3
PG	3.9	5.8	12.6	10.6	4.3	10.0	5.8	8.5	10.5
Significantly different groups									
AU1 × AU2	**	**	ns	ns	**	ns	**	ns	ns
AU1 × PG	ns	**	**	**	**	**	ns	**	**
AU2 × PG	ns	**	**	**	**	**	ns	**	**

AU1 – aeroponic unit 1; AU2 – aeroponic unit 2; PG – polycarbonate isolation unit. **Significantly different at a 0.01 probability level; ns – non-significant

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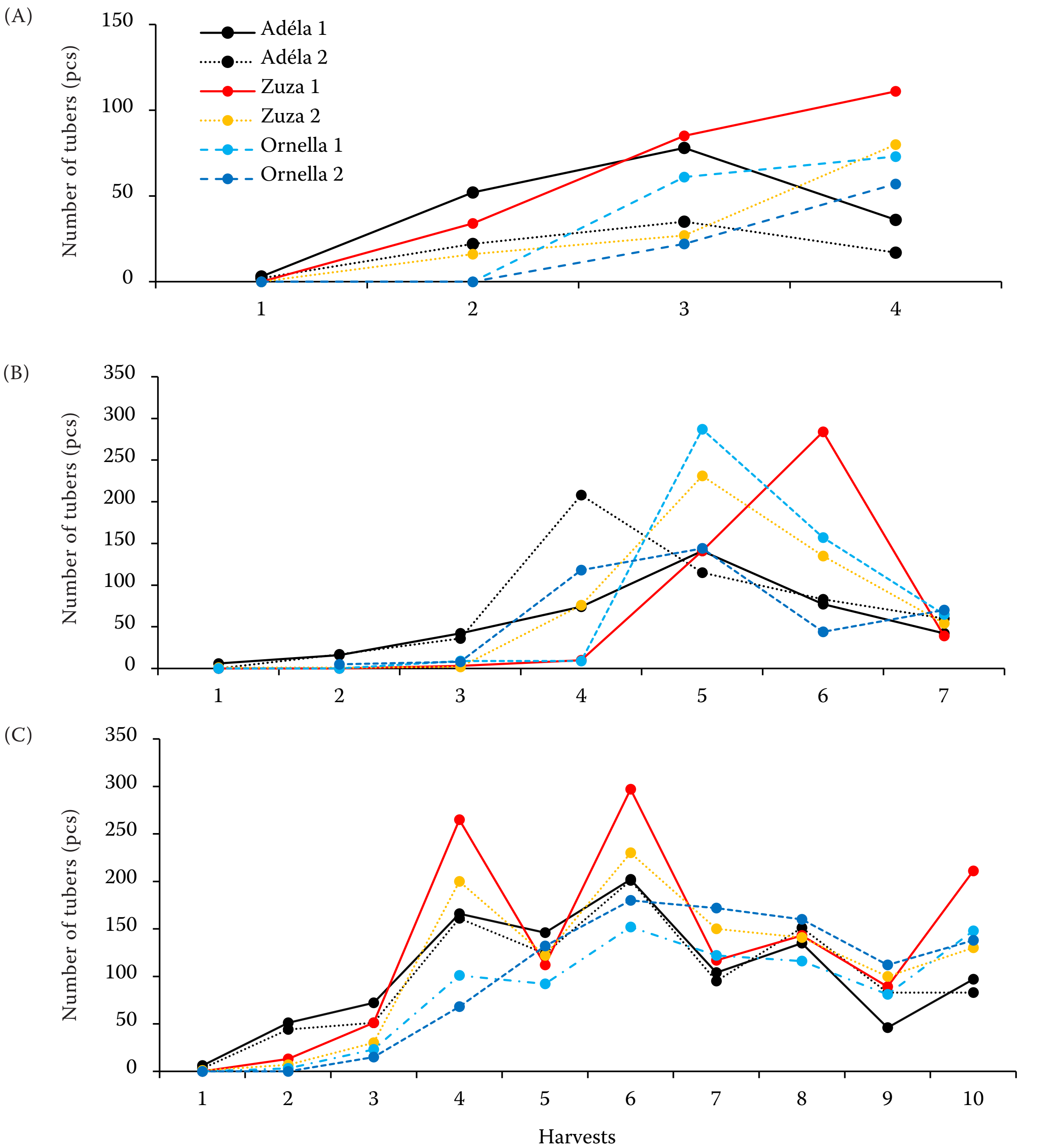

Figure 1. Numbers of harvested potato mini-tubers in aeroponic units in (A) 2019; (B) 2020 and (C) 2021. Adéla 1 – cv. Adéla in AU1; Adéla 2 – cv. Adéla in AU2; Zuza 1 – cv. Zuza in AU1; Zuza 2 – cv. Zuza in AU2; Ornella 1 – cv. Ornella in AU1; Ornella 2 – cv. Ornella in AU2; AU1 – aeroponic unit 1; AU2 – aeroponic unit 2

AUs was statistically significant. Here more tubers were formed in AU1 (19.5 per plant) compared to AU2 (14.4 per plant). The number of harvests (5–7) and harvested tubers for each cultivar and aeroponic unit in 2020 is shown in Figure 1B.

2021: In AU1, more tubers were formed in the cv. Adéla (average of 34.0 tubers per plant in AU1 compared to 33.7 in AU2) and cv. Zuza (average of 41.0 tubers per plant in AU1 compared to 36.3 in AU2) (Table 1). In AU2, more tubers were formed in the cv. Ornella (average of 30.7 tubers in AU2 compared to 25.6 in AU1). In AU1, there were significantly more tubers in the cv. Zuza compared to the cv. Ornella. This difference was statistically signifi-

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cant ($P \leq 0.01$). The number of successive harvests this year was 8–10 (Figure 1C). Significantly more tubers were formed in both AUs compared to PG (average number of tubers per plant: cv. Adéla – 12.6, cv. Ornella – 10.0, cv. Zuza – 10.5) (Figure 2). The differences were statistically significant, even for the cv. Ornella produced fewer tubers in AU1 than the other cultivars ($P \leq 0.01$).

When comparing the numbers of harvested tubers in individual AUs between 2019 and 2021, there was a year-on-year increase (Table 2). For AU1, the difference between 2019 and 2021 was statistically significant for all the cultivars we tested. The difference in the number of tubers between 2019 and 2021 was statistically significant for the cvs. Zuza and Adéla in favour of 2021. Between 2019 and 2020, the difference in favour of 2020 was statistically significant only for the cv. Ornella. In AU2, the difference between individual years within the cultivars was statistically significant for all cultivars and each year. During 2019 to 2021, the vegetation season of plants in AUs increased, and the number of harvested tubers also increased. This is in agreement with Çalışkan et al. (2021), who stated that the extension of the growing season is one of the main determining factors for increasing the yield of mini-tubers in aeroponics. The length of the growing cycle for potatoes is at least 4 months while also being cultivar-specific. In aeroponics, it is approximately 1–2 months longer than in field conditions (Otazú 2010). This is consistent with the presented experimental results, where the vegetation cycle duration in aeroponics ranged from 126 to 177 days. On the other hand, in the polycarbonate greenhouse, the vegetation period duration ranged from 51 to 63 days. The number of tubers can also be affected by successive harvests, as Farran and Mingo-Castel (2006) successively harvested aeroponic tubers at 10-day intervals. In the conventional system, only one harvest took place. Çalışkan et al. (2021) reported an average number of tubers in an aeroponic system of 19.85 tubers per plant at 25 plants/m^2. They found that the aeroponic system was more advantageous in terms of increasing the number of tubers both per plant and per unit area as well as the yield of tubers, while the conventional system yielded a higher average weight of tubers. Overall, the aeroponic system behaved better and provided a higher yield than the conventional system for all cultivars (between one to four times). Similarly, according to Abdullateef et al. (2012), the highest number of mini-tubers per plant, 40.82, was obtained with 25 plants/m^2. In that case,

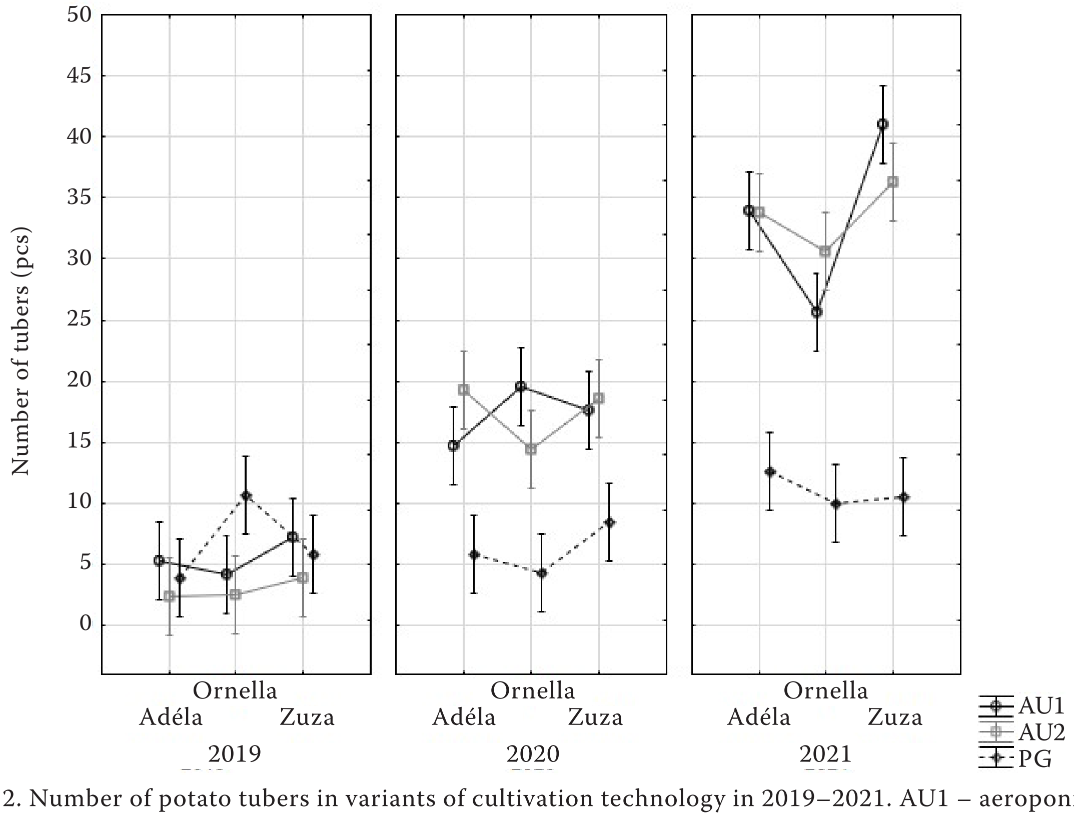

Figure 2. Number of potato tubers in variants of cultivation technology in 2019–2021. AU1 – aeroponic unit 1; AU2 – aeroponic unit 2; PG – polycarbonate isolation unit

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Table 2. The effect of experimental season and cultivation technology on the number of tubers in potato cultivars

Year	Cultivation technology								
	AU 1			AU 2			PG		
	cv. Adéla	cv. Ornella	cv. Zuza	cv. Adéla	cv. Ornella	cv. Zuza	cv. Adéla	cv. Ornella	cv. Zuza
The average number of tubers per plant									
2019	5.3	4.2	7.2	2.4	2.5	3.9	3.9	10.6	5.8
2020	14.7	19.5	17.7	19.2	14.4	18.5	5.8	4.3	8.5
2021	34.0	25.6	41.0	33.7	30.7	36.3	12.6	10.0	10.5
Significantly different groups									
2019 × 2020	ns	**	ns	**	**	**	**	**	**
2019 × 2021	**	**	**	**	**	**	**	ns	**
2020 × 2021	**	ns	**	**	**	**	**	**	**

AU 1 – aeroponic unit 1; AU2 – aeroponic unit 2; PG – polycarbonate isolation unit. **Significantly different at a 0.01 probability level; ns – non-significant

it was possible to harvest an average of 805 minitubers larger than 20 mm from one m^2. Regarding the number of tubers, the results of the experiment from 2020 and 2021 were close to the conclusions of other authors (14.4–41.0 tubers/plant) (Abdulateef et al. 2012, Rykaczewska 2016, Çalisçan et al. 2021).

In PG (Table 2), there was also a gradual increase in the number of tubers, except for the cv. Ornella, which in 2019 formed a number of tubers which surpassed the harvest in 2021. The cvs. Adéla and Zuza did gradually increase since 2019 by 2021. For the cv. Adéla, this difference was statistically significant both between 2019 and 2021 and between 2020 and 2021. For the cv. Zuza, differences were significant between all years.

The average weight of potato tubers. 2019: For the cv. Zuza, the average weight of tubers per plant was higher in AU1 (7.1 g) compared to AU2 (6.3 g) (Table 3). In contrast, the average weight of Adéla and Ornella was higher for AU2 (cv. Adéla 6.8 g, cv. Ornella 6.2 g) compared to AU1 (cv. Adéla 6.0 g, cv. Ornella 4.9 g). However, the differences between AUs were not statistically significant. In PG, the average weight of tubers per plant ranged from 22.7 g for the cv. Adéla to 32.0 g for the cv. Zuza. The difference between PG and AU was statistically significant ($P \leq 0.01$).

2020: The average weight of tubers per plant was higher in all cultivars in AU1 (cv. Adéla 7.5 g, cv. Ornella 3.0 g, cv. Zuza 5.0 g) compared to AU2 (cv. Adéla 6.1 g, cv. Ornella 2.7 g, cv. Zuza 2.0 g) (Table 3). The differences between AUs were not statistically significant, but the difference between PG and AUs was statistically significant ($P \leq 0.01$). The average weight of tubers in PG ranged from 22.4 g of the cv. Ornella to 37.3 g of the cv. Zuza.

2021: The average weight of tubers per plant was higher in all cultivars in AU1 (cv. Adéla 11.2 g, cv. Ornella 7.8 g, cv. Zuza 7.3 g) compared to AU2 (cv. Adéla 9.9 g, cv. Ornella 7.2 g, cv. Zuza 6.6 g) (Table 3, Figure 3). However, there were no statistically significant differences between the two nutrient solutions. Same as in previous years, the average weight of tubers per plant was statistically significantly higher in PG compared to AUs ($P \leq 0.01$). The average weight of tubers ranged from 31.7 g per plant in the cv. Zuza to 43.7 g per plant in the cv. Ornella (Table 4).

Rykaczewska (2016) reported an average weight of mini-tubers in an aeroponic system between 9 g and 10 g in two different planting densities, 36 and 42 plants/m^2. However, according to the author, tubers grown in the substrate were larger, with weights between 14.5 g and 21.6 g. In the present experiment, the average weight of tubers in AUs ranged between 2.0 g and 9.9 g. However, here the lower weight of tubers was influenced by choice to harvest smaller tubers in successive harvests. On the contrary, the average weight of tubers in PG was higher in the experiment than reported by Rykaczewska (2016). The size could be influenced by the cultivation technology (i.e., growing in the substrate in polycarbonate greenhouse *vs.* container experiments of Rykaczewska, or by the nature of the varieties used).

Çalışkan et al. (2021) stated that the aeroponic system was more advantageous in terms of increas-

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Table 3. Effect of nutrient solutions in aeroponics and cultivation technology on the average weight of tubers

Cultivation technology	cv. Adéla			cv. Ornella			cv. Zuza		
	2019	2020	2021	2019	2020	2021	2019	2020	2021
The average weight of tubers per plant (g)									
AU1	6.0	7.5	11.2	4.9	3.0	7.8	7.1	4.6	7.3
AU2	6.9	6.1	9.9	6.2	2.7	7.2	6.3	2.1	6.6
PG	22.7	31.6	41.9	32.0	22.4	43.7	26.3	37.3	31.7
Significantly different groups									
AU1 × AU2	ns	ns	ns	ns	ns	ns	ns	ns	ns
AU1 × PG	**	**	**	**	**	**	**	**	**
AU2 × PG	**	**	**	**	**	**	**	**	**

AU1 – aeroponic unit 1; AU2 – aeroponic unit 2; PG – polycarbonate isolation unit. **Significantly different at a 0.01 probability level; ns – non-significant

ing the number of tubers per plant and unit area and tuber yield, while a conventional system was more suitable for achieving higher tuber weight, as confirmed by the presented experimental results where the average tuber weight was higher in PG.

Regarding the effect of nutrient solution on tuber weight in AU1, statistically significant differences in weight for all monitored cultivars occurred only in 2020. In other years, there were no obvious trends in the effect of nutrient solution on tuber weight. The same was true for AU2. In contrast, in PG, the difference between the cultivars was statistically significant in all combinations within individual years. These results could be due to the fact that in

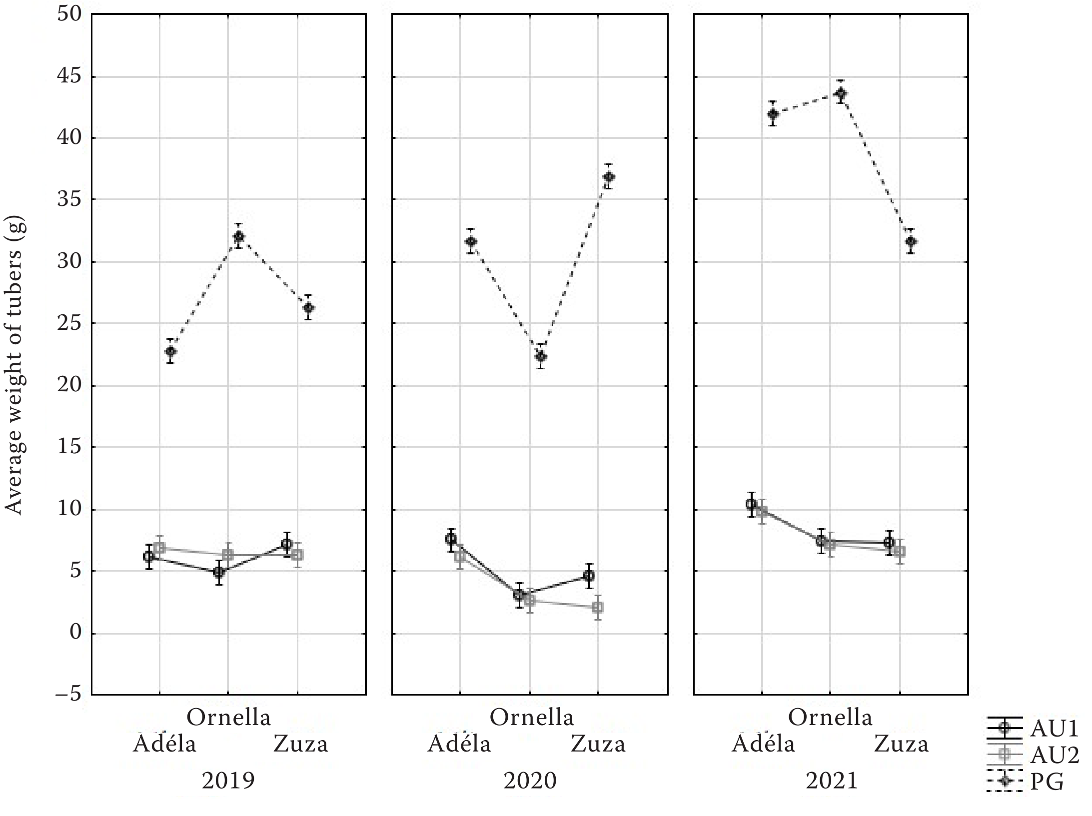

Figure 3. The effect of the potato cultivar and cultivation technology on the average weight of potato mini-tubers in 2019–2021. AU1 – aeroponic unit 1; AU2 – aeroponic unit 2; PG – polycarbonate isolation unit

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Table 4. Influence of potato cultivar on average tuber weight within individual variants of cultivation technology

Cultivar	Cultivation technology								
	AU1			AU2			PG		
	2019	2020	2021	2019	2020	2021	2019	2020	2021
The average weight of tubers per plant (g)									
Adéla (A)	6.1	7.5	10.4	6.9	6.1	9.9	22.7	31.6	41.9
Ornella (O)	4.9	3.0	7.5	6.2	2.7	7.2	32.1	22.4	43.7
Zuza (Z)	7.1	4.6	7.3	6.3	2.1	6.6	26.4	37.0	31.7
Significantly different groups									
A × O	ns	*	*	ns	*	*	*	*	*
A × Z	ns	*	*	ns	*	*	*	*	*
Z × O	*	*	ns	ns	ns	ns	*	*	*

AU1 – aeroponic unit 1; AU2 – aeroponic unit 2; PG – polycarbonate isolation unit. *Significantly different at a 0.05 probability level; ns – non-significant

AUs, tubers were harvested regularly after reaching a certain size rather than being influenced by the cultivar (Table 4). Only one harvest took place in PG after shoot senescence, which is why there were differences between the cultivars in all years. The different number of tubers at PG in individual years was caused by external environmental conditions, which in PG affected the development of tubers more than in the greenhouse where AUs were located.

According to Tessema et al. (2017), all crops have specific nutrient needs for optimal growth; even each potato cultivar may require a different nutrient solution. In the experiment, however, all cultivars responded similarly to the set conditions in all monitored growth parameters. However, each crop needs a specific optimal composition, electric conductivity values and nutrient solution pH, which affects fruit quality as well as the benefits of gradual harvests, as shown in studies on the benefits of growing tomatoes, peppers and lettuce in a greenhouse using technologies without substrate and hydroponics (Tzortzakis and Economakis 2008, Montesano et al. 2016, Amalfitano et al. 2017). Similarly, Buckseth et al. (2016) and Rykaczewska (2016) stated that optimisation of aeroponics technology is still necessary for specific environmental conditions and individual potato cultivars. Under the experimental conditions, the pH was adjusted between 5.5 and 6.5, and the conductivity ranged from 0.9 to 2.0 mS/cm; the temperature of the nutrient solution ranged from 15 to 20 °C, which was suitable according to the achieved results. Nevertheless, it is still necessary to prevent infestations by plant pests. In 2019, a massive infestation of plants by aphids occurred, which resulted in the premature end of that season and the failure of a substantial part of the tubers to fill out.

The technology of aeroponics was verified in a multi-year trial, during which scientific knowledge of its use for the production of healthy seed planting material was expanded.

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