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RESEARCH ARTICLE

Multiple *versus* single harvest comparison for two potato cultivars with an aeroponic system in Indonesia

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ABSTRACT

One of the main reasons for the high potato (*Solanum tuberosum* L.) tuber production in aeroponics is that tubers can be harvested repeatedly selectively without damaging the plant or disturbing the development of other tubers. This study aimed to explore the potential of multiple harvests to increase the number of potato tubers with an aeroponic system in Indonesia on two potato cultivars (‘Atlantic Malang’ and ‘Granola L’). The experimental design used a split plot design, namely the cultivars as the main plot and harvest system as the subplot with three replicates. Multiple harvest began at the age of 8 wk after transplanting (WAT) every 2 wk, while single harvest for ‘Granola L’ was carried out at the age of 12 WAT and ‘Atlantic Malang’ at the age of 16 WAT. The results showed that there were three clusters with a principal component analysis value of 87,3%, namely: 1) ‘Atlantic Malang’ with multiple harvests, 2) ‘Atlantic Malang’ with single harvests, and 3) ‘Granola L’ both single and multiple harvests. The high-growth ‘Atlantic Malang’ responded differently to the harvest system, while the low-growth ‘Granola L’ responded similar to the harvest system. Multiple harvests not only increased number of total tubers by 36%, but also improved tuber quality with adjustable tuber size and reduced the number of rotten tubers per plot by 96% in ‘Atlantic Malang’ and 100% in ‘Granola L’.

Key words: Aeroponic, bacterial wilt, cultivar, harvest system, high temperature, *Solanum tuberosum*.

INTRODUCTION

Limited seed availability and expensive seed prices cause most potato (*Solanum tuberosum* L.) farmers in Indonesia to use tuber seeds from previous harvest selections (Dianawati et al., 2023a). If the harvest results are felt to have decreased drastically, farmers will only buy new seeds after more than three planting seasons. This condition underlies the low potato production in Indonesia which in 2024 was 18.82 t ha^{-1} and has not been able to keep up with the national potato consumption of 2.82 kg per capita per year. With the limited availability of quality seeds, this certainly requires the seed production method which provide more seeds in large quantities at affordable prices (Dianawati et al., 2023b; Dianawati and Fahmi, 2024), because current seed production methods, both conventional and hydroponic, can only produce less than five tubers per plant (Dianawati et al., 2013).

Aeroponics can be a promising solution to increase seed availability compared to conventional and hydroponics (Balena et al., 2021; Broćić et al., 2022; Singh et al., 2025). Aeroponics allows the provision of nutrients in the form of mist directly to the roots of plants suspended in the air, so that the roots will not lack oxygen (Tengli and Raju, 2022) and ensure that nutrients are easily absorbed by plants (Garzón et al., 2023). Thus, aeroponics is not only effective in exploiting the vertical space of the greenhouse, but also optimizes the development of roots, tubers, and foliage (Otazú, 2010; Singh et al., 2025). The advantages of the aeroponic system include increased root aeration, efficient use of water and nutrients, and reduced risk of soil-borne diseases (Broćić et al., 2022). In addition, aeroponics in the tropics has the advantage of being able to produce virus-free seeds and free of soil-borne diseases (Broćić et al., 2022).

One of the main reasons for the high tuber production in aeroponics is that tubers can be harvested repeatedly selectively without damaging the plants or disrupting the development of other tubers (Broćić et al., 2022; Hasrak and Zarghami, 2023) through a window on the side of the aeroponic box (Balena et al., 2021). The increase in the number of tubers with multiple harvests in aeroponics compared to single harvests was reported to be 100%-250% (Oraby et al., 2015). However, multiple harvest treatment in aeroponic systems in the tropics is at risk of being susceptible to disease (Kuncoro et al., 2021) such as bacterial wilt (*Ralstonia solanacearum,* RS) (Dianawati et al., 2024). Dianawati et al. (2024) stated that RS is one of the obstacles to the implementation of aeroponics in Indonesia. This is because RS effectively develops in high temperature areas. In addition, multiple harvest of tubers will leave wounds from cuts, making them easily infected by RS, because RS easily enters plant tissue through wounds (Yuliar et al., 2015). Meanwhile, each cultivar is thought to have different genetic characteristics, such as short cultivar plants that are not very tall but produce tubers earlier, results in low tuber production, but aeroponic can extend its growth period to produce more tubers (Tierno et al., 2014; Broćić et al., 2022). Several research also studied on harvest frequencies in aeroponics and its results vary between once every 7-14 d (Farran and Mingo-Castel, 2006; Factor et al., 2007), but there has not been any research report yet that focuses on discussing the potential for multiple harvest in aeroponics compared to single harvest in tropical areas, especially in Indonesia. This study aimed to explore the potential of multiple harvests to increase the number of potato tubers with an aeroponic system on two different potato cultivars in Indonesia.

MATERIALS AND METHODS

The study was conducted in the greenhouse of the Potato Seed Center, Pangalengan, Bandung, West Java, Indonesia. The experimental design used a split plot design, namely potato (*Solanum tuberosum* L.) cultivars as the main plot ('Atlantic Malang' and 'Granola L') and harvest system as subplots (single harvest and multiple harvest) with three replicates.

The aeroponic tank was made of fiberglass with a width of 1.0 m, a length of 13.0 m, and a height of 0.6 m. The aeroponic tank was lined with Styroform with a thickness of 2.5 cm and covered with black and silver mulch. A 1000 L nutrient drum was connected to the aeroponic tank with a 15 m long and 13 mm diameter pipe. Each tank consisted of two nutrient pipes with a distance between sprinklers of 60 cm. The AB mix nutrients specifically for potatoes were flowed from the nutrient drum with a booster pump to be sprayed in the form of mist to the roots through sprinklers. After hitting the roots, the nutrients fell due to gravity and returned to the nutrient drum. Nutrients were maintained in the range of electrical conductivity (EC) 1-2 mmho cm^{-2} using an EC meter and pH 6-7 using a pH meter. In addition, the nutrient water in the tank was sterilized with 3% H_2O_2 at a concentration of 2 L 1000 L^{-1}.

The apical root cuttings used were from the 1st and 2nd parent plantlets for 'Granola L' and from the 3rd to 5th parent plantlets for 'Atlantic Malang'. The cuttings used had 5-7 leaves, strong stems, 10-15 cm tall, and healthy roots. The nursery planting medium was sterilized rice husk charcoal: Compost (1/1 v/v). Two weeks later the seeds were transferred to aeroponics. One experimental unit measuring 1 m × 0.5 m with a planting distance of 20 × 20 cm^2 or 15 plants. Before planting, the roots of the cutting seedlings were rinsed with H_2O_2 and drained for 2 min. Then soaked in a solution of *Pseudomonas fluorescens* and *Bacillus subtilis* consortium microbes with 3 g L^{-1} for 10 min (Dianawati et al., 2024). Rockwool as a plant support was soaked in a 2 mL L^{-1} H_2O_2 solution and injected with microbial solution at 1 and 2 wk after transplanting (WAT). Microbial solution was sprayed on the top of the plant once a week since 3 WAT. Pest and disease control was carried out if there was an indication of attack using chemical pesticides. The application range of chemical pesticides and microbial solutions was 3 d.

Multiple harvests were started at the age of 8 WAT every 2 wk, while single harvests for 'Granola L' were carried out until the age of 12 WAT and 'Atlantic Malang' until the age of 16 WAT. Tubers were harvested when they were more than 5 cm in diameter. Tubers were harvested in the morning when the nutrient spray from the nozzle stops for 3 min in an intermittent interval of 7 min. Tubers were harvested by cutting the stolons using a sterile cutter that has been dipped in 70% alcohol and then the stolon cut marks and tuber cut marks were sprayed again with 70% alcohol.

The variables observed per plant were plant height, number of tuber initiations, number of primary stolons, number of sessile tubers, number of tubers growing from stolons, number of aerial tubers, total number of tubers, number of large tubers (> 10 g), medium (5-10 g), and small (< 5 g), tuber diameter, tuber weight, weight per tuber, number of abnormal tubers, and number of rotten tubers. The variables observed per plot were disease attack, tuber weight, number of tubers, number of rotten tubers, and number of abnormal tubers. Sessile tubers were tubers that did not grow from the tip of the stolon, but were attached to the primary stolon with short secondary stolons less than 3 cm. Aerial tubers were tubers that grew out of Styroform. Analysis of N nutrient absorption using the Kjeldahl method, P using UV-Vis spectrophotometry, K and Ca using the atomic absorption spectrophotometry method (Eviati et al., 2023). Nutrient uptake test samples were conducted on all plants at the ages of 8, 10, 12, 14, and 16 WAT depending on the cultivar. Nutrient water testing on Ralstonia solanacearum (RS) was conducted every week following the method in Dianawati et al. (2024).

Data were analyzed using ANOVA by SAS 9.0 Program version 9.4 and if there was a significant difference, it was continued with the Duncan test with a 95% confidence level. Testing between observed variables used the principal component analysis (PCA) test with the RStudio program version 4.4.3 (PBC, Boston, Massachusetts, USA; http://www.rstudio.com). The packages used for PCA analysis were gplots, ggplot2, FactoMiner, factoextra, corrplot, and cluster.

RESULTS

Climate

The mean air temperature in the morning showed 20.76 °C, while in the afternoon below 25.00 °C at 24.68 °C and during the day above 25 °C at 26.78 °C (Figure 1a). Meanwhile, the mean humidity in the morning was quite high at 90.46%, while in the afternoon it was 64.69% and, in the afternoon, it was 74.26% (data not shown). The mean temperature in the aeroponic box in the morning was the lowest at 16.8 °C, but during the day it was the highest at 28.63 °C, but the mean temperature fluctuation in the afternoon between the greenhouse, aeroponic box, and nutrients was almost the same at around 23-24 °C (Figure 1b).

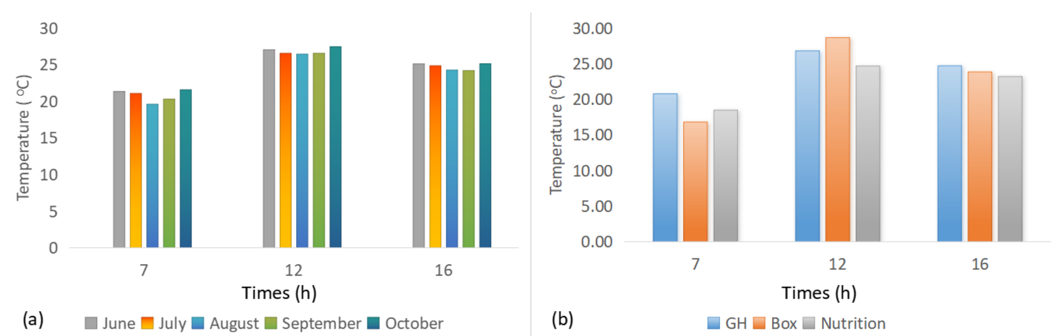

Figure 1. Fluctuations in mean air temperature in the greenhouse (a) and mean temperature fluctuations in greenhouse (GH), aeroponic box, and water nutrition (b) at 7, 12, and 16 h during the research.

Interaction between harvest frequency and cultivar

The interaction between harvest frequency and cultivar affected tuber weight per plant and plot, weight per tuber, number of big tubers, abnormal tuber, and rotten tuber per plant, and number of tubers, rotten tuber, and abnormal tuber per plot (Table 1). Multiple harvest of 'Atlantic Malang' caused high tuber weight per plant and plot, number of big tubers per plant, number of tubers per plot, but number of abnormal tubers per plot was also high, but number of rot tuber per plant and plot and number of abnormal tubers per plot were low

(Table 1). Meanwhile, although 'Atlantic Malang' single harvest had high weight per tuber, number of rotten tubers per plant was also high with low number of big tubers per plant (Table 1). 'Granola L' with multiple harvest caused high number of abnormal tubers per plant with lower tuber weight per plot than 'Atlantic Malang' in all harvest frequency treatments. The low tuber weight per plot in 'Granola L' multiple harvest was due to its low weight per tuber, although the number of tubers per plot was quite large compared to 'Atlantic Malang' single harvest (Table 1). Meanwhile, 'Granola L' single harvest had the highest number of rotten tubers and abnormal tubers per plot, as well as the lowest tuber weight and number of big tubers per plant, tuber weight and number of tubers per plot (Table 1).

Table 1. Interaction among observed variables. Data was transformed with *Log (x+4). CV: coefficient of variance. Numbers followed by the same letter in a row are non-significantly different using Duncan's test ($p < 0.05$).

	Harvest frequency				
	Multiple		Single		
Observed variables	Atlantic Malang	Granola L	Atlantic Malang	Granola L	CV (%)
Tuber weight per plant	180.7^{a}	101.4^{bc}	114.8^{ab}	52.8^{c}	28.6*
Weight per tuber	12.01^{b}	7.4^{b}	28.9^{a}	13.2^{b}	26.9*
Number of big tubers per plant	6.3^{a}	3.3^{b}	0.4^{c}	1.6^{c}	29.8*
Number of abnormal tubers per plant	1.2^{b}	6.6^{a}	1.8^{b}	3.9^{ab}	27.1*
Number of rot tubers per plant	0.2^{b}	0.0^{b}	1.8^{a}	0.0^{b}	28.3*
Tuber weight per plot	3257.9^{a}	1058.4^{c}	2603.5^{b}	390.2^{d}	29.7*
Number of tubers per plot	251.8^{a}	121.3^{b}	86.9^{b}	32.5^{c}	30.8*
Number of rot tubers per plot	0.4^{b}	0.1^{b}	11.2^{b}	391.1^{a}	26.2*
Number of abnormal tubers per plot	15.4^{a}	0.0^{b}	0.0^{b}	15.0^{a}	35.1*

Peak uptake of N and P in 'Atlantic Malang' multiple harvest occurred at 10 WAT, while in 'Granola L' at 8 WAT and then in all treatments N and P nutrient uptake decreased (Figures 2a and 2b). Potassium uptake in all treatments decreased over time (Figure 2c), while Ca uptake increased over time (Figure 2d).

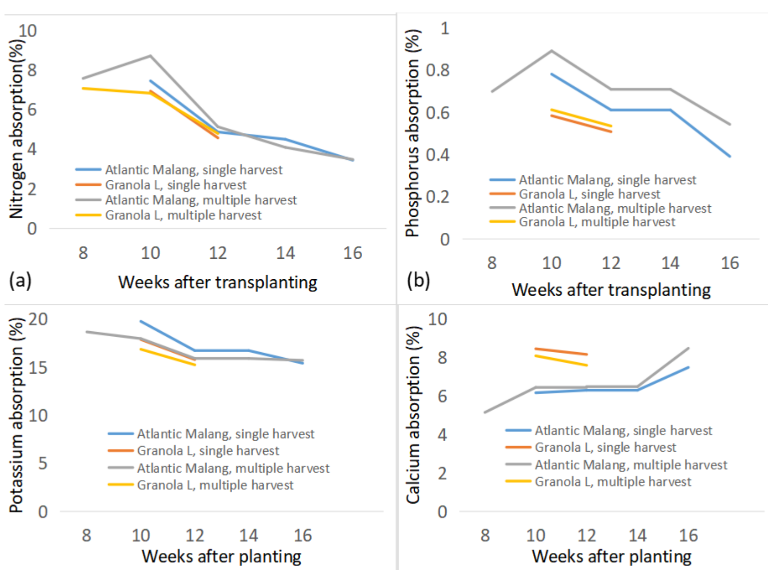

Figure 2. Nitrogen (a), P (b), K (c), and Ca (d) absorption in single and multiple harvest on two cultivars in aeroponic system.

Single effect of harvest frequency and cultivar

'Atlantic Malang' had a higher plant height (2-7 WAT), number of stolons (4-6 WAT), number of initiation tubers 6 WAT (Figure 3), but lower *Alternaria* attack than 'Granola L' (Table 2). 'Atlantic Malang' had vegetative growth from both plant height and high number of stolons, so the initiation time was faster at 6 WAT than 'Granola L'. *Alternaria* attack on 'Atlantic Malang' was also lower because of its high growth so it was more resistant to *Alternaria* disease attack than 'Granola L' (Table 2, Figure 3).

Multiple harvest increased the number of sessile tubers, tubers from stolons, small tubers, but had lower tuber diameters than single harvest (Table 2). Multiple harvest caused the number of sessile tubers, tubers from stolons and small tubers to be greater than single harvest. The large number of small tubers caused multiple harvest to have smaller tuber diameters than single harvest (Table 2).

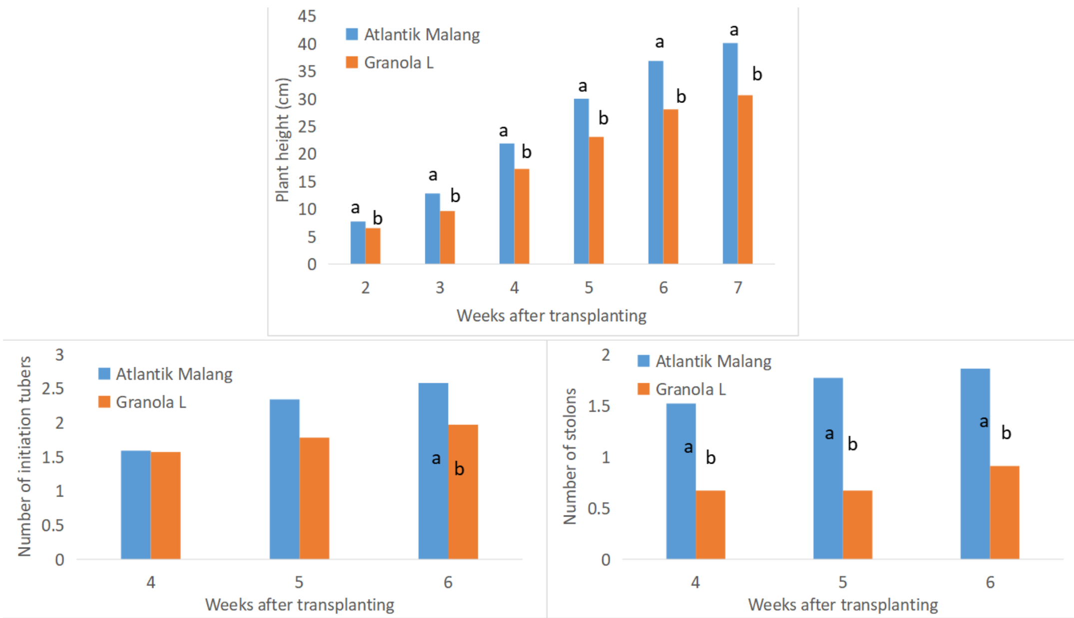

Figure 3. Plant height (a), number of initiation tubers (b), and number of stolons (c) on two cultivars in aeroponic system. Adjacent tube followed by the different letter are significantly different using Duncan's test ($p < 0.05$).

Table 2. Single effect of cultivar and harvest frequency on observed variables. Data was transformed with *Log (x+4). Numbers followed by the same letter in a row are non-significantly different using LSD's test ($p < 0.05$). CV: coefficient of variance.

	Cultivar		Harvest frequency		
Observed variables	Atlantic Malang	Granola L	Multiple	Single	CV (%)
Number of tubers from stolon per plant	3.78	3.57	5.06^{a}	2.29^{b}	25.7*
Number of aerial tubers per plant	5.44	0.19	0.51	5.13	34.1*
Number of total tubers	15.21	8.69	14.63	9.25	36.7*
Number of medium tubers	6.84	1.79	2.68	5.95	29.1*
Number of small tubers	4.16	4.43	7.19^{a}	1.39^{b}	27.2*
Tuber diameter	30.77	27.87	25.78^{b}	32.86^{a}	23.1*
Percentage of *Alternaria* attack	2.87^{b}	68.28^{a}	34.75	36.41	32.7*

Principal component analysis results

There were three clusters with a PCA value of 90% (Figures 4 and 5). The first cluster was the multiple harvest of 'Atlantic Malang' which had a high number of total tubers per plot in the first quadrant and it was in first quadrant (Figure 4). The second cluster was the 'Atlantic Malang' single harvest which was influenced by the weight per tuber, number of rotten tubers per plant, number of abnormal tubers per plant, and number of medium tubers per plant in the fourth quadrant and it was in the fourth quadrant (Figure 4). The third cluster was the 'Granola L' cluster, both single and multiple harvests, which had in common a high percentage of *Alternaria* attacks and a high number of abnormal tubers per plant (Figure 4). 'Granola L' single harvest had additional special characteristics in the form of a high number of rotten tubers per plot in the third quadrant, while 'Granola L' multiple harvest had additional characteristics in the form of a high number of abnormal tubers per plot in the second quadrant (Figure 4). Even though 'Granola L' was in two different quadrants, they were close in position and focus on the variables of the number of abnormal tubers and percentage of *Alternaria* attacks and based on PCA biplot, they were combined into one cluster, while the harvest system in 'Atlantic Malang' forms a different cluster (Figure 5).

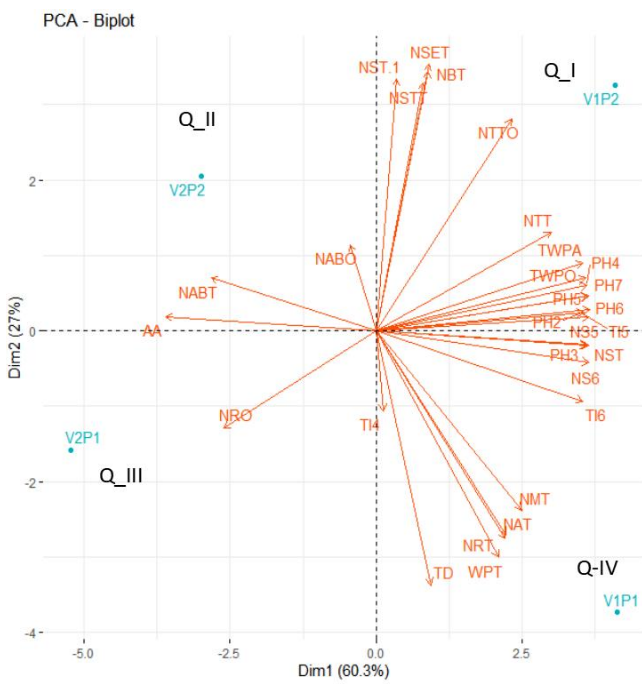

Figure 4. PCA biplot for various treatment combinations and observation variables. PH2/3/4/5/6/7: Plant height at 2/3/4/5/6/7 wk after transplanting; NS4/5/6: number of stolons at 4/5/6 wk after transplanting; TI4/5/6: tuber initiation at 4/5/6 wk after planting; NSET: number of sessile tubers; NSTT: number of tuber from stolon; NAT: number of aerial tubers; NTT: number of total tubers; TWPA: tuber weight per plant; WPT: weight per tuber; NBT: number of big tubers; NMT: number of medium tubers; NST: number of small tubers; NABT: number of abnormal tubers; NRT: number of rotten tubers; TWPO: tuber weight per plot; NTTO: number of total tuber per plot; NABO: number of abnormal tubers per plot; NRO: number of rot tubers per plot; TD: tuber diameter; AA: percentage of *Alternaria* sp. attack; V1: 'Atlantic Malang' cultivar; V2: 'Granola L' cultivar; P1: single harvest; P2: multiple harvest.

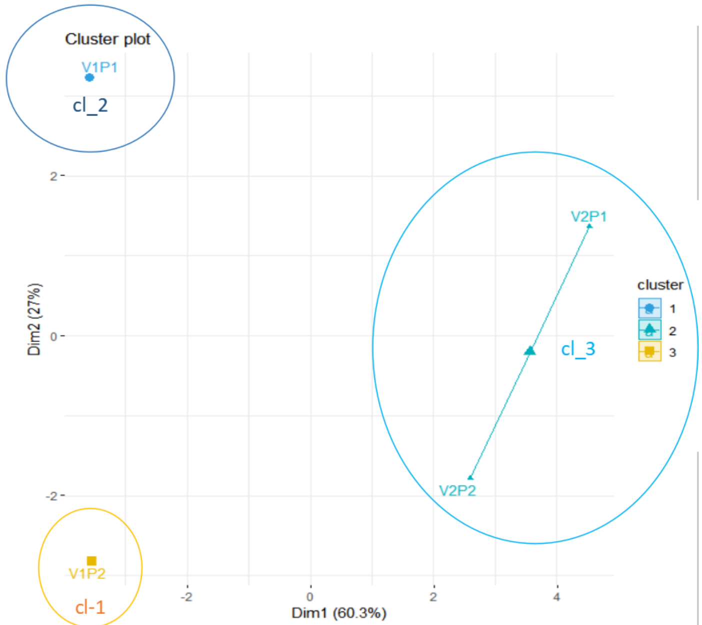

Figure 5. Clusters plot for various treatment combinations and observation variables. V1: 'Atlantic Malang' cultivar; V2: 'Granola L' cultivar; P1: single harvest; P2: multiple harvest; cl_1: first cluster; cl_2: second cluster; cl_3: third cluster.

DISCUSSION

Several treatments were carried out in this study to overcome *Ralstonia solanacearum* (RS) wilt, namely before entering the aeroponic system, the water was chemically sterilized using H_2O_2 and in the aeroponic system, the consortium of *Pseudomonas fluorescens* and *Bacillus subtilis* microbes were used. Hong et al. (2013) reported that the use of H_2O_2 on tomatoes could control RS bacterial wilt. Dianawati et al. (2024) reported that soaking the consortium of *P. fluorescens* and *B. subtilis* microbes could control RS wilt by 85%. Although tuber harvesting was carried out 3-5 times depending on the cultivar, weekly RS testing of the nutrients used in this research did not result in RS contamination. This showed that multiple harvests could be carried out in tropical areas with special treatments as carried out in this research. Thus, maintaining sterile nutrients and sterile cultivation activities including sterile harvesting methods were the main keys to the success of multiple harvest in aeroponic system in tropical areas, such as Indonesia, which had bacterial wilt problem in high temperature.

The results of this research indicated that the number of stolons at the beginning of harvest for both 'Atlantic Malang' and 'Granola L' at 4 to 6 WAT ranged from 0-2 (Table 2; Figure 3). Meanwhile, the number of primary stolons in the aeroponic system should be able to reach more than 10 with the number of secondary stolons more than 10 (Dianawati et al., 2013). When viewed from plant growth, the height of plants in this research only ranged from 30-40 cm at 7 WAT depending on the cultivar (Figure 3), while plant growth in aeroponics should be able to reach more than 50 cm (Dianawati et al., 2013). When viewed from the nutrient absorption, the absorption of N nutrients in this research was only 3%-9%, P 0.3%-0.9%, and K 15%-19% (Figures 2a-2c). Nutrient absorption in this study continued to decrease for both N, P, and K in line with the increasing age of the plant (Figure 2). When viewed from the harvest frequency, the harvest interval in this research was quite long, once every 2 wk because the tuber growth was slow to be re-harvested compared to the research of Farran and Mingo-Castel (2006) which was once every 7 d. From these descriptions, it could be concluded that plant growth in both cultivars in this research was not optimal even though it could produce the number of tubers ranging from 8-15 per plant depending on the treatment (Table 2). Meanwhile, the number of tubers resulting from aeroponic research in Indonesia varied depending on the treatment tested, namely less than 20

(Ishartati et al., 2017; Kuncoro et al., 2021; Sugiyono et al., 2021a; 2021b) and more than 20 (Dianawati et al., 2013; Silva Filho et al., 2018; Sumarni et al., 2022).

The maximum mean air temperature range in this research was 26.78 °C and the minimum mean temperature was 20.78 °C indicating that the air temperature was still in the range below 30 °C (Figure 1a). Kuncoro et al. (2021) stated that areas with a maximum temperature range of 30 °C and a minimum temperature of 15 °C were suitable for potato growth compared to areas with stable temperatures of around 24 °C. However, the mean maximum temperature in the aeroponic box in this research could reach 28.63 °C, even though the minimum mean temperature was around 16.8 °C (Figure 1b). The maximum temperature in the aeroponic box as a place to grow was quite high compared to the best rooting temperature for potatoes of around 18 °C (Oraby et al., 2015). Chang et al. (2006) reported that a rooting temperature of 25 °C in aeroponics could suppress root growth compared to a temperature of 20 °C. Thus, the high temperature during the day in the aeroponic box even though the air temperature was quite low in this research (Figures 1a and 1b), could be a limiting factor for suboptimal plant growth, so that the tubers produced were also not many. Temperature was a critical factor that greatly determined potato production in tropical areas. High temperatures could suppress root growth, so that nutrients could not be absorbed by plants to support plant growth (Oraby et al., 2015). This could be seen from the low nutrient absorption value in this research (Figure 2). Whereas on the other hand, the absorption of N, P, and K in potato plants was very important for plant growth, tuber development, and optimal harvest yields (Wang et al., 2024). Meanwhile, the nutrients used in this research were AB mix solutions commonly sold on the Indonesian market for potato plants. Sugiyono et al. (2021b) reported that AB mix nutrients produced more tubers than Otazú nutrients and Farran nutrients. However, the diversity of AB mix content sold on the Indonesian market did not seem to guarantee the availability of nutrients for plants. Thus, choosing the right nutrient formulation was very important in aeroponics (Chang et al., 2008). Muhibuddin et al. (2018) reported that the AB mix formulation in the form of N (NO_3^- 185; NH_4^+ 40), P 80, K 250, Ca 150, Mg 80, S 100, Fe 8.0, Cu 0.4, Mo 0.20, Mn 2.0, Zn 0.4 and B 0.8 mg L^{-1} was the best for aeroponics in Indonesia so that it could increase the number of tubers by more than 20 per plant.

The plant growth, the number and weight of 'Granola L' tubers were lower and the number of abnormal tubers was greater than of 'Atlantic Malang' (Table 2, Figure 3). It happened because 'Granola L' cuttings at the beginning of growth showed less able to adapt quickly when transplanted to the aeroponic system. Even though the number of cuttings propagated by the two cultivars was different (1st and 2nd parent plantlets for 'Granola L' and the 3rd to 5th parent plantlets for 'Atlantic Malang'), both cuttings were still in juvenile period and actively forming shoot. Wang et al. (2024) stated that as long as the seedlings could maintain their juvenile period, the seedlings could be a good source of seedlings to produce many stolons and many tubers. Thus, this showed that differences of number of cuttings propagated between two cultivars in this research was not the reason why the 'Atlantic Malang' was superior than 'Granola L'. Furthermore Muhibuddin et al. (2018) reported that 'Atlantic Malang' produced more tubers than 'Granola L' because of its pervasive root system. In this research, 'Atlantic Malang' had a spreading root system compared to 'Granola L' which clumped together (Figure 6). It can be the reason why Atlantic Malang' cuttings had quicker growth characteristics than 'Granola L' when adapting to the new environment in aeroponics. The same thing also happened in the research by Muhibuddin et al. (2016), so that 'Atlantic Malang' was considered to easily absorb nutrients and oxygen around the roots to produce higher plant and tuber growth than 'Granola L'. Thus, cultivars with specific root growths as genetic characteristic also affected the success of multiple harvests in aeroponics (Hasrak and Zarghami, 2023; Singh et al., 2025). In this research, 'Atlantic Malang' could also be harvested more up to five times to 16 WAT, while 'Granola L' was only three times to 12 WAT (Figure 3), because it adjusted the length of the growing period of the plant cultivar. Broćić et al. (2022) reported that the long-duration 'Kennebac' and 'Agria' consistently continued to produce tubers throughout the growing period in aeroponics compared to the short-duration 'Cleopatra' and 'Sinora'. The higher growth and the number of stolons of 'Atlantic Malang' in this research also had lower percentage of *Alternaria* attacks than 'Granola L' (Table 2). This was indicated by the location of the 'Atlantic Malang' quadrant which was in the same plane as the growth of plant height and the number of stolons (Figure 4). 'Atlantic Malang' vegetative growth in the form of tall plants and healthy plants from disease attacks (Table 2, Figure 3) would produce assimilates during plant growth, so that it had a longer plant life to produce more large and medium-sized tubers than 'Granola L' (Table 2, Figure 3). Thus, vigorous and healthy plant growth in aeroponics could increase the number of tubers produced (Broćić et al., 2022; Singh et al., 2025).

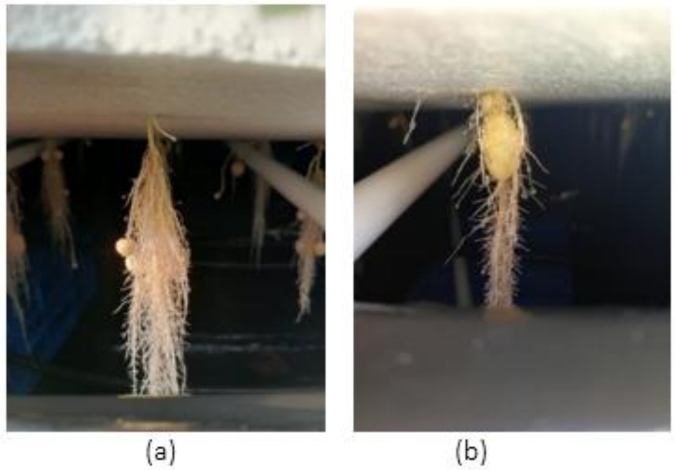

Figure 6. Root performance of ‘Atlantic Malang’ (a) and ‘Granola L’ (b) in aeroponic system at 4 wk after transplanting.

Each cultivar in this research responded differently to the system harvest treatment, resulting in three clusters of treatment combinations with a fairly high PCA value of 87.3% (Figures 3 and 4). The high-growth ‘Atlantic Malang’ responded differently to the harvest system, while the low-growth ‘Granola L’ responded similar to the harvest system, namely with a high number of abnormal tubers and percentage of *Alternaria* attack (Figure 4). This could be seen from the position of the combination of ‘Granola L’ treatment combinations which were close together compared to the ‘Atlantic Malang’ treatment combination which were far apart (Figure 5).

‘Atlantic Malang’ with multiple harvest as the first cluster had a high number of tubers per plot (Figure 4). This was because the weight per tuber of ‘Atlantic Malang’ multiple harvest was not too large (12 g), but the number was many, so that cumulatively it produced a high tuber weight per plant and per plot (Table 1). Harvesting tubers in aeroponics could increase the formation of stolons to form new tubers, so that the number of tubers per plant and tubers m^{-2} increased (Farran and Mingo-Castel, 2006). Harvesting large tubers was a fairly efficient assimilate distribution strategy where with higher plant growth (Table 2), the plant divided the assimilate into a large number of tubers. Harvesting large tubers could stimulate the growth of new tubers and the remaining tubers would grow larger (Farran and Mingo-Castel, 2006; Factor et al., 2007; Abdullateef et al., 2012; Balena et al., 2021; Broćić et al., 2022). This was because large tubers were storage organs that were the strong sinks to compete for all assimilates produced during plant growth (Saidi and Hajibarat, 2021; Zierer et al., 2021). Tsoka et al. (2012) stated that tuber harvesting in multiple harvests in aeroponics could increase the formation of new lateral tubers as a result of breaking apical dominance.

‘Atlantic Malang’ with single harvest as the second cluster had a high weight per tuber character (Table 1) and high tuber diameter (Figure 4). This could occur because of the high growth of ‘Atlantic Malang’ (Figure 3), so that they could accumulate a lot of assimilates for tuber growth. However, because the focus was on the weight and large diameter of tubers without the disposal of large tubers as the main sink, the number of tubers was not as much as multiple harvest (Table 1, Figure 4). The large weight of tubers in this treatment combination also caused large tuber lenticels to form and were easy to crack due to continuous nutrient spraying. This was thought to cause a higher number of rotten tubers per plant compared to multiple harvest (Table 1). Lenticels on tubers produced in the aeroponic system were formed due to high humidity (Farran and Mingo-Castel, 2006). Salt accumulation from nutrients could injure the surface of the tubers (Calori et al., 2018). In addition, the condition was also exacerbated by the high temperature in the aeroponic box during the day (Figure 1b). Thus, the inefficiency of ‘Atlantic Malang’ with high vegetative growth and producing many assimilates without carrying out multiple harvests actually had a negative impact on the number of rotten tubers.

Tuber growth in high temperature conditions could encourage the formation of tubers with irregular or abnormal shapes (Silva Filho et al., 2018) and the formation of sessile tubers and small tubers (Roumeliotis et al., 2012). However, the number of abnormal tubers in this research was also influenced by the physiological response of each cultivar and the different frequency of harvests (Table 1, Figure 4). The number of abnormal tubers per plot of 'Atlantic Malang' multiple harvest was the highest compared to other treatments (Table 1), because the growth of many tubers was due to high plant growth with short stolons, but was blocked by Styrofoam as a plant support medium, so that it pressed the Styrofoam and formed tubers with abnormal shapes. Repeated tuber harvesting in 'Atlantic Malang' could use up stolon energy, so that the growth of tubers that cluster was only around the stolon and did not go up. This was different from the 'Atlantic Malang' single harvest which was influenced by the number of aerial tubers (Figure 4), because only one harvest with a lot of stolon energy so that the tubers grew up freely.

Multiple harvest of with low plant height growth in 'Granola L' could increase tuber weight and number of tubers per plot, number of large tubers, and reduce the number of rotten and abnormal tubers per plot compared to single harvest (Table 1). However, both treatment combinations, 'Granola L', both single and multiple harvests were included in the third cluster with a high number of rotten and abnormal tubers (Figure 4). Calcium was very important for tuber quality, especially in strengthening cell walls and preventing diseases such as hollow heart and black spot, so that they did not rot easily (Gondwe et al., 2019). However, in this research, the high Ca in 'Granola L', both single and multiple harvests at 10 and 12 WAT compared to 'Atlantic Malang' (Figure 2d), could not help prevent tuber rot. Thus, rotten tuber was not caused by cultivar factors alone, but rather by continuous nutrient spraying. In addition, 'Granola L' in single and multiple harvests had many abnormal tubers due to seedling stress at the beginning of transplanting with low vegetative growth and short stolons, while the single harvest treatment on 'Granola L' worsened the rotten condition due to continuous spraying of nutrients on the lenticels that opened in aeroponic box conditions with high temperatures during the day. This confirmed the novelty of this research, namely that multiple harvests not only increased the number of total tubers by 36% (Table 2), but also improved tuber quality with adjustable tuber size and reduced the number of rotten tubers per plot by 96% in 'Atlantic Malang' and 100% in 'Granola L' (Table 1). Concerns about bacterial wilt attacks occurring in the multiple harvest treatment did not occur in this study.

The benefits of multiple harvesting were not only on the high growth in "Atlantic Malang", but also on the low growth in 'Granola L'. By doing multiple harvests, mature tubers were harvested on time before their quality decreased. This was important to prevent rot that often occurred due to over maturity or tissue degradation. Tubers that were harvested on time and did not rot were expected had a higher storage life, better seed quality, better market value, and reduced post-harvest losses. The physical and chemical quality of tubers (such as water content, tissue hardness, and starch content) were also maintained better when harvesting was done gradually and selectively. In addition, reducing tubers with multiple harvests could reduce the temperature around the roots. This was because basically each tuber would respire which produced heat and could increase the temperature (Sumarni et al., 2022). Thus, multiple harvests could also reduce competition between tubers for growing space.

CONCLUSIONS

There were three clusters with a principal component analysis value of 87.3%, namely 'Atlantic Malang' with multiple harvests which had a high total number of potato tubers per plant and per plot, 'Atlantic Malang' with single harvests with high weight per tuber and number of rotten tubers per plant, and 'Granola L' both single and multiple harvests with a high number of abnormal tubers and rotten tubers. The high-growth 'Atlantic Malang' responded differently to the harvest system, while the low-growth 'Granola L' responded similar to the harvest system. Multiple harvests not only increased number of total tubers by 36%, but also improved tuber quality with adjustable tuber size and reduced the number of rotten tubers per plot by 96% in 'Atlantic Malang' and 100% in 'Granola L'.

Author contributions

Conceptualization: M.D., K.K.H., I.S. Methodology: M.D., K.K.H., I.S., B.S., P.E.R.P. Prepared material: K.K.H., H.H. Conducted the experiment: M.D., K.K.H., I.S., B.S., A.N., I.C., I.B.R., Y.H., A.A., H.H., P.E.R.P., R.I, S.H., M.R., J.P. Data curation: M.D., K.K.H., I.S., B.S., A.N., I.C., I.B.R., Y.H., A.A., H.H., P.E.R.P. Writing-original draft: M.D., K.K.H. Writing-review and editing: M.D., K.K.H., B.S., I.C., Y.H., H.H. Analyzed data: M.D., Y.H. All co-authors reviewed the final version and approved the manuscript before submission.

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