Method of pump, pipe, and tank selection for aeroponic nutrient management systems based on crop requirements

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Abstract

The system-specific selection of aeroponic nutrient system components, specifically pumps, pipes, and tanks, is very important to improve system efficiency and minimize costs, as these components vary for different systems with different crop water requirements and design specifications. In this study, methods were suggested for determining the most suitable sizes of pumps, pipes, and tanks based on the plant water consumption and irrigation interval targeted to improve the usual procedures to design an aeroponic nutrient management system, and applied to a case. Factors affecting the size calculation are discussed, and calculation methods were suggested based on basic hydraulic principles. A recycle-type aeroponic nutrient management system, cultivating 500 plants in 21 plant beds, was considered for a case study. Application of the size calculation methods in the case study showed that an irrigation pump with a 37 Lmin^{-1} flow rate at 900 kPa capacity and nutrient pumps with a 5 Lmin^{-1} flow rate at 40 kPa capacity with 19-mm-diameter pipes were required to deliver the mixed nutrients and supply stock solutions into the mixing tank, along with nutrient mixing, stock nutrients, and distilled water tanks of 750, 40, and 685 L, respectively. Calculation was demonstrated to show the variations in the sizing of the pumps, pipes, and tanks by number of plants. Validation tests were performed for the selected irrigation pump capacity, and the results showed that the Nash-Sutcliffe efficiency coefficient (NSE), coefficient of determination (R^2), and root-mean-square error (RMSE) values were 0.410, 0.98, 0.109 Lmin^{-1} and 0.775, 0.99, 34.91 kPa for flow rate and pressure, respectively. The case study also showed that these sizing procedures increased the plant bed coverage efficiency of the irrigation pump by 33%, while increasing the nutrient mixing tank size by 133%. This study would provide useful information on the efficient sizing of pumps, pipes, and tanks for minimizing costs and maximizing crop production in aeroponic nutrient management systems.

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Introduction

Hydroponics, a soilless, water-based crop production system using nutrient-rich solutions, has been gaining in popularity in recent years due to water and nutrient savings, quick growth, high yields, and low rates of root-borne diseases (Pignata *et al*., 2017). However, the usual procedures to design and select the size of the nutrient management system components still needs to be improved to supply adequate nutrients to plants and to increase the production efficiency. Nutrient system components, specifically pumps, pipes, and tank size, need to be optimized for specific crops because they cannot be universal for crops with different nutrient and water requirements. Among the different types of hydroponic crop production systems, aeroponics (periodic spray) is an improved technique that saves a substantial amount of water and nutrients by spraying a mixed nutrient solution directly into the plant root zone (Jones, 2016). The critical aspects of this technique are the droplet types, spray method, irrigation interval, and root zone coverage. For these purposes, the selection of the proper sized pumps, pipes, and tanks is essential and the methods of selection also need to be improved for increasing nutrient management efficiency, leading to minimized installation, operating, and maintenance costs, and maximized crop production.

Different crops water requirements, target cultivation area coverage, application methods, and layouts are important factors for selection of pump, pipe, and tank sizes. For example, the water consumption ranges of leafy vegetables, herbs, and climbing plants are 0.30-0.50, 0.5-1, and 3 Lday^{-1}plant^{-1}, respectively. The mean greenhouse floor area in Korea and Japan are 0.33 and 0.5 hectares, respectively, whereas it is 10–50 hectares in the

Netherlands and the USA (Kozai, 2015). Undersized pumps, pipes, and tanks cannot meet the water and nutrient requirements of plants. On the other hand, large pumps, pipes, and storage tanks entail huge initial installment costs and increased operating and maintenance costs (Marchi *et al*., 2017). Irrigation strategies also influence the size selection related to these components. Farmers sometimes abandon their cultivation due to lack of water and nutrient storage, faulty supply systems, and high operating and maintenance costs. The selection methods of the proper pump size, considering flow rate and pressure, to decrease operating and maintenance costs and optimize the water supply, have been reported in several studies (Moran, 2016). Pumps should provide sufficient pressure to overcome the operating pressure of any specific system to supply fluid at the required flow rate. Raza (2013) mentioned that the selected pump flow rate and pressure must be equal to, or more than, the calculated requirement. Sometimes a properly sized pump cannot provide adequate water or nutrients due to the improper size of the supply pipe (Van Zyl *et al*., 2004). Jadrnicek and Jadrnicek (2016) used two methods to identify the required pipe size, namely, the velocity limit method for high-pressure systems and the use of a friction loss table for gravity-fed systems. After computing the relevant parameters (velocity limit and friction factor), pipe size was determined using a pipe characteristics chart provided by the manufacturer. However, Trimmer and Hansen (1997) emphasized the initial installation and operating (variable) costs of irrigation pipe network design. The optimum supply of water and nutrients not only depends on the pump and pipe, but also storage availability. For a greenhouse, crop water demand is usually 12-17 Lm^{-2} of a growing area per day, especially in summer. In a plant factory, the crop water demand depends on the hydroponic culture media and crop species (Jones, 2016). In recent years, single- and multi-objective optimization methods have been commonly used for tank sizing (Batchabani and Fuamba, 2012; Kurek and Ostfeld, 2013). The Washington State Department of Health (2009) also mentioned a tank sizing process (considering more factors) for ensuring a sufficient amount of water at any time in their *Water System Design Manual*. The amount of water stored needs to be equal to or greater than the demand for the next circulation step.

In hydroponic cultivation systems, nutrient mixing, and target solution preparation are critical issues because excessive supply of nutrient components could make the mixed solution toxic, and less supply could cause nutrient deficiencies, both finally degrading plant growth. Besides this, improper irrigation pump size may not be able to maintain optimum nozzle pressure during nutrient spray, which could result in poor root zone coverage in the aeroponic cultivation systems. The pipe and tank sizes also affect the availability of nutrients and water. Several studies have been conducted for the optimization and automation of aeroponic crop cultivation. However, very limited research has been focused on the improvement of usual selection procedures of the pumps, pipes, and tanks of aeroponic nutrient management systems. Experience-based estimation or improper design of any hydroponic nutrient management system components can degrade the accuracy and precision of nutrient management, and increase costs for installation, operation, and maintenance due to low performance and efficiency. Therefore, in this study, methods were suggested for determining the most suitable sizes of pumps, pipes, and tanks based on the plant water consumption and irrigation interval targeted to improve the usual procedures to design an aeroponic nutrient system.

Materials and methods

Overview of aeroponic nutrient system components

The components of an aeroponic nutrient system are shown in Figure 1. A high-pressure irrigation pump is used for spraying the mixed nutrient solution and low-pressure nutrient pumps are used for supplying the distilled water, stock nutrients, and used solutions into the mixing tank through pipes. Nutrient mixing, distilled water, and used solution tanks are common, but the number of stock solution tanks depends on the system design.

Factors affecting the pump, pipe, and tank size selection

The capacity of a pump (flow rate and pressure) needs to be optimized for specific systems, as using the same pump for different arrangements would reduce system efficiency. Before selecting an irrigation pump, the target coverage area, total head or pressure against this area, desired flow rate, suction lift, pump working process, and application need to be considered (Moran, 2016; Marchi *et al*., 2017). The number of nutrient pumps used in any nutrient management system depends on the number of tanks of stock nutrient solutions, distilled water, and used solution. Although Jung *et al*. (2015) used a multi-channel peristaltic pump to supply eight different stock solutions to a nutrient mixing tank, distilled water was supplied using a separate pump. Individual meter pumps were used by Cho *et al*. (2017) to inject stock solutions, distilled water, and used nutrient solution. Pipe size is directly related to the flow rate and pressure of a pump. The factors that should be considered during pipe size selection are flow velocity, pressure loss related to pipe roughness, stress level, stability and fatigue failure, cost of installation, ease of maintenance, and expansion capacity (Trimmer and Hansen, 1997; Van Zyl *et al*., 2004). Among these, flow rate, roughness, and stress level are generally given priority over the other factors. Adequate water and nutrients cannot be supplied by properly sized pumps and pipes if storage is scarce. Tank size depends on the crop species and water requirements (Table 2), irrigation schedule, and the target coverage area (Table 1 and 2) (Bos *et al*., 2008). The number of tanks depends on the design spec-

Table 1. Factors affecting the selection of pump, pipe, and tank size.

Factors	Pump	Pipe	Tank
Flow	Flow rate	Flow velocity	Water consumption rate
Pressure	Pressure head	Pipe friction and stress	Crop species
Coverage	Coverage area	Supply method	Number of crops
Application	Application process	Easy maintenance	Water supply schedule

ification and purposes. Distilled water and nutrient mixing tanks are common in every hydroponic system and they are bigger than stock solution tanks because stock solutions are highly concentrated. Jung *et al*. (2015) used four small separated tanks for different stock nutrient solutions in their research, besides the use of two stock solution tanks for holding commercial stock nutrients A and B is also available. In the case of recycling hydroponic nutrient systems, an additional used solution tank is required for collecting unused nutrient solution and then ensuring that the solution is filtered and sterilized. System-specific size selection of pumps, pipes, and tanks is very important for adequate, and efficient hydroponic nutrient management. The common considerations for these ctomponents are shown in Table 1.

Methods of size calculation

Pump capacity

Pump size selection is a vital issue because pumps use 25-50% of the total energy depending on the system application. A pump with insufficient capacity reduces system efficiency and a pump with too large a capacity causes damage. An oversized pump also wastes energy and results in higher operating costs. Therefore, pumps need to have a size (flow rate and pressure) that matches their operational purpose.

Irrigation pump

In an aeroponic nutrient management system, mixed nutrient solution is supplied to the plant root zones via nozzles placed in plant beds in different tiers. Therefore, a high-pressure pump is required. The flow rate of the pump depends on the nozzle flow rate and the total number of nozzles. In this study, the nozzle flow rate (Q_N) was calculated using the flow rate equation ($Q = AV$, where A is the cross-sectional areas and V is the velocity of the solution) (King and Wisler, 1974) and considering the selected nozzle orifice diameter (d_N) and working pressure (P_N).

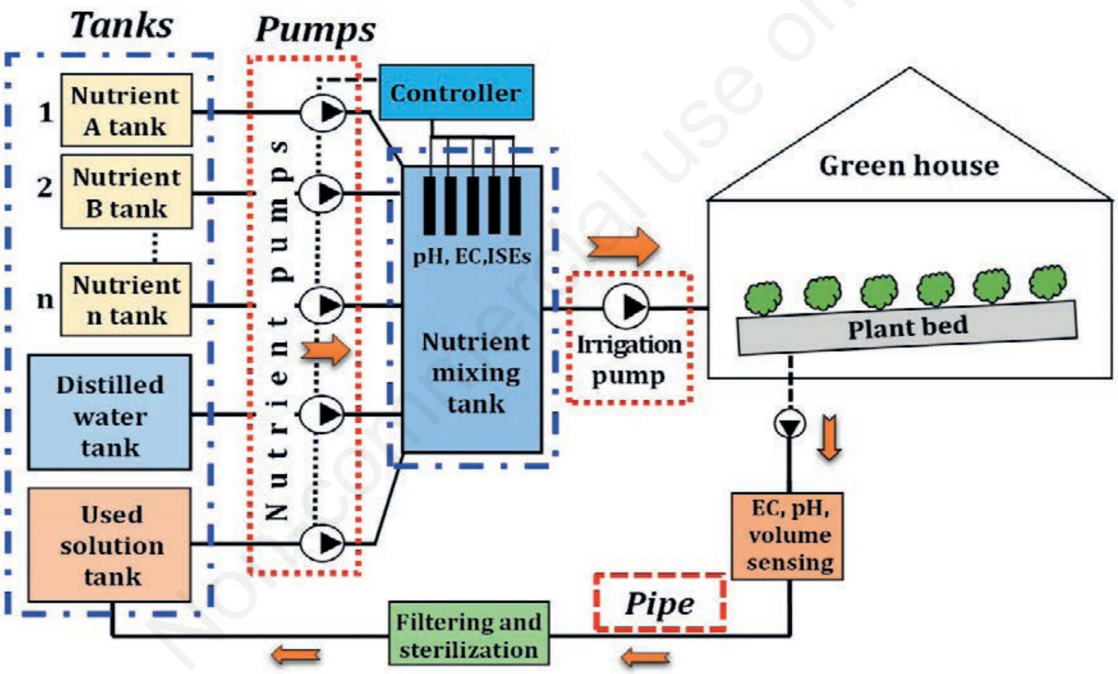

Figure 1. Schematic diagram of a general aeroponic nutrient management system.

Table 2. Water consumption range of different crops cultivated using hydroponic system.

Crop type	Crop species	Water consumption (L day^{-1} plant^{-1})	References
Leafy vegetable	Chinese cabbage (*Brassica rapa*)	0.35~0.58	Lira *et al*., 2015
	Kale (*Brassica oleracea*)	0.30~0.50	Lira *et al*., 2015
	Lettuce (*Lactuca sativa*)	0.45~1.00	Jones, 2016
	Spinach (*Spinacia oleracea*)	0.48~0.6	Jones, 2016
Shrub plant	Tomato (*Solanum lycopersicum*)	0.5~1.00	Jones, 2016
	Pepper (*Capsicum annum* L.)	0.56~0.75	Amalfitano *et al*., 2017
	Potato (*Solanum tuberosum*)	0.5~0.7	www.fao.org
	Strawberries (*Fragaria x ananassa*)	0.35~0.38	Jones, 2016
Climbing plants	Cucumber (*Cucumis sativus* L.)	Up to 3	www.fao.org
	Melon (*Cucumis* spp.)	Up to 3	www.fao.org

$$Q_N = 0.0666 \times d_N^2 \times \sqrt{P_N} \quad (1)$$

$$Q_{Pump} = Q_N \times N_N \quad (2)$$

$$P_{pump} = P_N + P_{loss} + EI \quad (3)$$

$$P_{loss} = P_{fric.} + P_{fit.} \quad (4)$$

$$El = f\frac{L}{D} \times \frac{8Q^2}{gD^5\pi^2} \quad (5)$$

$$L = N_T \times N_{PB} \times (H_B \times D_{BB}) \quad (6)$$

The pressure was calculated based on Bernoulli's equation, where the nozzle working pressure, pipe loss, and elevation loss were considered. Darcy's formula and the Darcy-Weisbach law (King and Wisler, 1974) were followed for pipe loss and elevation determination, respectively. Pipe friction ($P_{fric.}$) is related to the inner surface, velocity, pressure of flow, length, and diameter of the pipe used in the system. Pipe fittings ($P_{fit.}$) loss is caused by flow direction changing devices such as elbows, reducers, control valves, and backflow prevention devices; the related values were obtained from standard pipe loss charts (Bird, 2007).

Nutrient pumps

Nutrient pumps supply distilled water, stock nutrients, and used solution to the nutrient mixing tank. General atmospheric pressure/head is acceptable for these pumps and the desired flow rate is controlled by flow rate control devices such as solenoid valves. The flow rate and pressure head of these pumps were calculated using the volumetric pump flow rate and the Darcy–Weisbach formula (King and Wisler, 1974), respectively.

$$Q_{Pump} = V_l \div t \quad (7)$$

$$P_{pump} = H_s + H_D + (P_{RT} - P_{RES}) \quad (8)$$

The atmospheric pressure changes with height and the pressure difference due to the pumping height always being too small, which can be neglected. Therefore, P_{RT} - P_{RES} = 0.

Pipe size

Pipe size selection depends on the fluid velocity limit and friction factor (Van Zyl *et al.,* 2004). The velocity limit is considered for the size selection of high-pressure main pipelines and friction factor is considered for the size selection of gravity-fed lateral pipelines (Jadrnicek and Jadrnicek, 2016). These two factors were computed using the following formulas and the required pipe size was identified by matching with the pipe characteristics chart provided by the manufacturer.

$$F_f = [0.2083 \times (100/C)^{1.852} \times Q^{1.852} \div d^{4.866}] \times 0.433 \quad (9)$$

$$v = 0.408(Q \div d^2) \quad (10)$$

Tank size

Plants mostly die due to water shortage. A storage tank should meet the operating water demand, ensuring supply during system failure and reserves for emergencies (Batchabani and Fuamba, 2012). A properly sized tank improves the overall supply efficiency; otherwise, increases the pipe installation and the operating costs (Vamvakeridou-Lyroudia *et al*., 2007). The storage tank volume consists of the operational volume (V_O), equalizing volume (V_E), standby volume (V_S), fire suppression volume (V_{FS}), and dead volume (V_D) (HDR Engineering, 2001). Fire suppression volume (V_{FS}) has been omitted in this study. Usually, tanks for distilled water, stock solutions, and mixed nutrients storage are used in an aeroponic system. The number of stock solution tanks varies with system specification. The methods for tank size selection are discussed below.

Volume of nutrient mixing tank

Volume of mixing tank = Operational vol. + Equalizing vol. + Standby vol. + Dead vol.

$$V_{MT} = V_o + V_E + V_s + V_D \quad (11)$$

The operational volume (V_O) of the nutrient mixing tank is the volume of the stock solutions and water, which plants consume for their physical growth per unit of time (Table 2). In the case of a recycling system, the operational volume could be calculated from the difference between the volume of nutrients supplied and the volume of nutrients returned. If the source is at risk of failing to meet the water system demand, the equalizing volume (V_E) helps to ensure that the demand is met. Standby volume (V_S) ensures supply reliability if the source fails or there is sudden demand that is higher than expected. The water uptake rate of the crops depends on various factors such as lighting period, humidity, evapo-transmission, plant age, growth stage, and nutrient composition, which were all considered to be constant.

Operational volume (V_O) = Vol. of nutrients supplied – vol. of nutrients returned
= (Nozzle flow rate × total number of nozzles × total spray time) – (Nutrient supply – crop water consumption) (12)

Equalizing volume (V_E) = (PHD-Qs) × (150 min)
Standby volume (V_S) = 2 days × *ADD* × N_{PB} (for a single source)
Dead volume (V_D) = 5% of the total volume

Volume of stock solution tank

$$V_{ST} = (V_{MT} \times C_T) \div C_S \quad (13)$$

Stock solutions are usually kept 100 times higher in concentration than the desired nutrient concentration level. Distilled water is added to ensure the required volume of the stock solution. Using the dilution theory ($C_1V_1 = C_2V_2$), the stock solution tank size was calculated.

Volume of distilled water tank

$$V_{DWT} = (V_{MT} - V_{ST}) \quad (14)$$

The volume of the distilled water tank was determined by subtracting the stock solution tank volume from the nutrient mixing tank volume.

Validation of the selection methods (case study)

A recycle-type hydroponic nutrient management system, cultivating 500 plants in 21 plant beds, was considered for a case study.

The layout of the nutrient management system has been shown in Figure 2A and the photo of the considered plant factory (3×7 m^2) in Figure 2B. The nutrient management system consisted of two subsystems: i) a stock nutrient solution supply subsystem consisting of distilled water, stock nutrients, and tanks for used solution, nutrient pumps, valves, and pipes for supplying the respective solutions to a mixing tank; and ii) a mixed nutrient solution supply subsystem consisting of a nutrient mixing tank, irrigation pump, pipes, nozzles, and plant beds. First, the stock nutrient solution and distilled water were injected into the mixing tank through nutrient pumps. After preparation, the desired mixed nutrient solution was supplied to the plant beds through the irrigation pump, pipes, and nozzles. The used nutrient solution was returned to the mixing tank from the used solution tank after filtration and sterilization.

This plant factory had four shelves with three tiers per shelf. Each tier had three plant beds, and the tiers were 550 mm apart from each other. The 36 plant beds were capable of growing 864 plants at a time. Details of the existing components of the plant factory are shown in Table 3. The plant bed layout, where each plant bed had 24 planting positions, is shown in Figures 3 and 4. Each plant bed contained six foggy spray nozzles (with 0.4-mm-diameter orifices) that sprayed fine mist nutrient solution on the plant roots for 120 s at 900 s intervals. The water requirement of Chinese cabbage was considered during the size calculation of pump, pipe, and tank.

The ambient environment of the plant factory has a strong influence on the selection of the nutrient management system component sizes. Lighting period, temperature, wind speed, water availability, plant species, and their physical attributes have proportional relationships with evaporation. Increasing evaporation increases the plant water and nutrient uptake rate, which also has proportional relationships with pump, pipe, and tank sizes. Table 4 shows the assumed range of ambient environment parameters used in the size selection calculations. Validation tests were performed for the selected irrigation pump capacity, and the Nash-Sutcliffe efficiency coefficient (NSE), regression analysis (R^2), and root-mean-square error (RMSE) were calculated. The NSE varies between −∞ and 1.0 showing how well the measured *versus* simulated data are fitted to the 1:1 line. R^2 indicates the degree of collinearity among variables and the range is 0~1. RMSE is used to compute the differences between the predicted and observed values. In general, a method/model can be considered as satisfactory when the value of NSE and R^2 are greater than 0.5 (Krause *et al*., 2005; Golmohammadi *et al*., 2014).

Table 3. Components specification of the plant factory used in the case study.

Item	Model	No. of item	Specification	Material
Plant bed	LCSPGPC-002, Parus, Daejeon, Korea	36	L×W×H (mm^3): 900×600×150 24 plants in each plant bed	PVC board
Nozzle	PJ15, Bete, MA, USA	5×36	Orifice dia. (mm): 0.4 Flow rate (Lmin^{-1}): 0.273	Stainless Steel
Pump	8095-902-260-Shurflo, CA, USA	12	Pressure head (kPa) : 970 Flow rate (Lmin^{-1}): 6	Zinc Plated Steel
Pipe	N2-4-12×9-20, Hyogo, Japan	-	Outside×inside dia. (mm): 12×9 Maxi. working pres. (MPa): 2	Nylon
Tank	LCSPGPC-002, Parus, Daejeon, Korea	12	L×W×H (mm^3): 550×350×350 Water holding capa. (L): 60	PVC Board

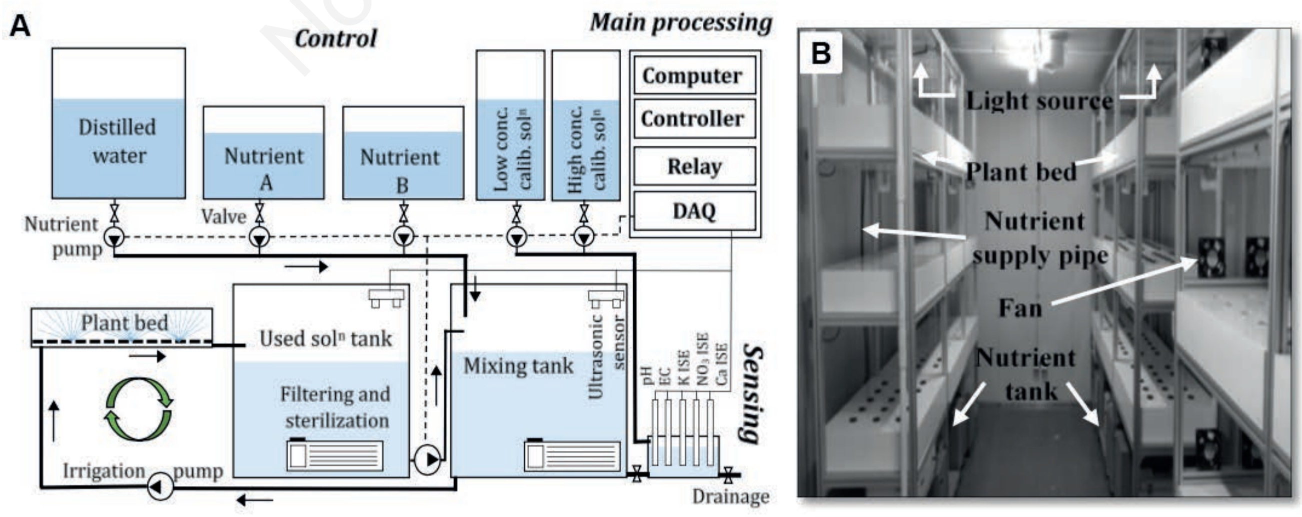

Figure 2. Case study: layout of the existed aeroponic nutrient management system (A), and photo of the considered plant factory (B).

Results

Size calculations

Pump capacity

In this study, nutrient pumps supplied water and stock solutions at a pressure of 1 atm for preparing the target nutrient solution, which was delivered to the plants' root zones via nozzles at a high pressure head and flow rate using an irrigation pump.

Irrigation pump

According to equations (2) and (3), the required irrigation pump flow rate for each plant bed was 1.11 Lmin^{-1} or 1.85×10^{-5} m^{3}s^{-1}, and the pump pressure was 900 kPa, when nozzle pressure, pipe loss, and elevation were 300 kPa, 5.55 kPa, and 0.647 kPa, respectively, as shown in Table 5.

Nutrient pumps

Usually, distilled water and used nutrient solution are supplied by individual pumps, but stock solutions are replenished using either multi-channel peristaltic pumps (Jung *et al*., 2015) or individual meter pumps (Cho *et al*., 2017). However, a nutrient pump with a 1.5 Lmin^{-1} flow rate at 100 kPa capacity was selected based on the other case study parameters. The flow rate and pressure changed according to the valve or other controller devices based on the system design specifications.

Pipe size

In this study, the pipe size was calculated based on the velocity limit and friction factor values. The velocity limit and friction factor were found to be 1.158 ms^{-1} and 1.207 kPa, using equations (9) and (10), respectively. The required pipe size was identified by matching these velocity limit and friction factor values with the pipe characteristics chart provided by the manufacturer. The recommended pipe size for mixed nutrient solution and stock nutrients supply were 12 mm and 6 mm, respectively (Table 5).

Tank size

The operational volume of the nutrient mixing tank was calculated according to equation (12), based on a 0.19 Lmin^{-1} nozzle flowrate, 6 nozzles per plant bed, a 192 min day^{-1} spray time, and a 0.4 Lday^{-1}plant^{-1} water consumption for Chinese cabbage plants. The calculated volume of the nutrient mixing tank was $34.27 \approx 35$ L for each plant bed (for 24 plants), which included operating (9.60 L), equalizing (3.84 L), standby (19.2 L), and dead (1.63 L) volumes (Table 5). Using equations (13) and (14), the calculated tank volumes for stock solutions and distilled water were $2.33 \approx 2.5$ L (based on 3000 ppm stock solution) and $32.5 \approx 35$ L, respectively. The volumes were calculated per plant bed per day.

Size selection for the case study

Size selection methods for pumps, pipes, and tanks were applied to the aeroponic nutrient management system that was designed. For 21 plant beds containing 500 Chinese cabbage plants, a flow rate of 37 Lmin^{-1} with a 900 kPa capacity irrigation pump, a flow rate of 5 Lmin^{-1} with a 40 kPa capacity nutrient pump, a 19-mm-diameter pipe and nutrient mixing, stock solution, and distilled water tanks of 735, 50, and 735 L, respectively, were required, as shown in Table 5.

Discussion

Pump, pipe, and tank size calculations

Irrigation pump capacity depends on nozzle flow rate and pressure. Usually, fine mist droplets of 0.11-0.24 mm (ASABE, 1999) are better for plant growth. The standard misting nozzle orifice sizes are 0.15, 0.20, 0.30, 0.40, and 0.50 mm. In this study, a 0.4-mm-diameter nozzle was used. This nozzle works from 200 to 2758 kPa, but for a full spray angle pattern, nozzles need to operate

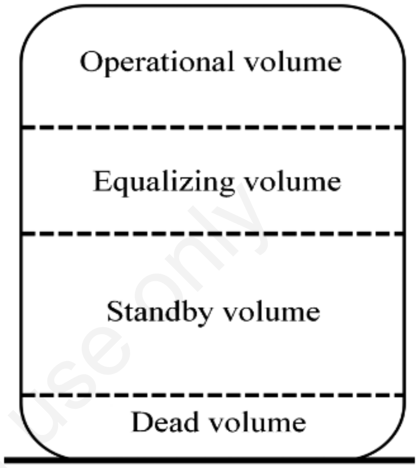

Figure 3. Cross sectional view of a storage tank.

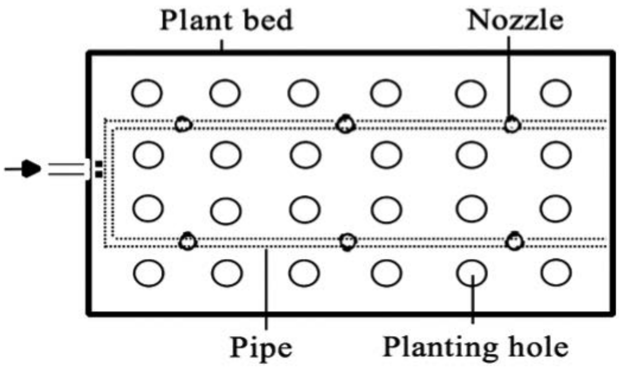

Figure 4. Plant bed of the plant factory with different components.

Table 4. Ambient environment condition during validation of the selection procedures.

Parameter	Assumptive range
Lighting time (day/night hours)	14/10
Temperature (°C)	20~24
Humidity (%)	60~70
CO$_2$ (ppm)	1000~1200
Air movement	Steady state
Irrigation coverage (%)	100
Crop	Chinese cabbage (*Brassica rapa*)
Water consumption rate	Similar rate for every plant

at $\geq$300 kPa. As a high pressure head reduces the pump flow rate, the minimum nozzle pressure (300 kPa) and related flow rate (0.19 Lmin^{-1}) were selected for the fine mist droplets. The validation results for pump pressure and flow rate are also shown. In this study, the existing pump could provide 4.86 Lmin^{-1} at a pressure of 325 kPa to cover four plant beds without changing the nozzle pressure or droplet conditions. BETE (2013) showed similar procedures for pump size calculation for a given system, where the required pump capacity was 374.72 Lmin^{-1} at 182.02 kPa. The nozzle operating pressure of the system was very low (48 kPa) and the nozzle orifice was big (63.5 mm), so a high flow rate with a low-pressure pump was required in that system. However, in our aeroponic system, high pressure with a low flow rate pump was required to deliver a very fine droplet. Moran (2016) also emphasized the system head when specifying any pump, which should provide the required flow to overcome the hydraulic resistances.

Friction losses are also critical aspects in the pipe size calculation. In this study, pipe size was selected after considering all kinds of resistance factors (*e.g.*, bends, valves, tees, and sharp entry) along with pipe material. Jadrnicek and Jadrnicek (2016) used similar procedures for calculating the pipe size for an application involving harvested rainwater. However, some researchers suggested considering fluid characteristics, separator location, and structural analysis before any pipeline design.

Tank size selection for any water supply system requires the surety of demand management, adequate storage, and support in case of system failure and emergencies, along with the required flow rate. In this study, water storage for fire emergency was excluded. In the review by Batchabani and Fuamba (2012), similar factors were suggested for consideration to ensure optimal tank size selection. However, multi-objective models, genetic algorithms were preferred in other studies for ensuring system efficiency (Fang *et al.*, 2010). Tank sizes in hydroponic systems varies with plant species, as the water consumption range of leafy vegetables such as Chinese cabbage (*Brassica rapa*), kale (*Brassica oleracea*), lettuce (*Lactuca sativa*), and spinach (*Spinacia oleracea*) is 0.30–0.50 Lday^{-1}plant^{-1}, and climbing plants such as tomato (*Solanum lycopersicum*), potato (*Solanum tuberosum*), and pepper (*Capsicum annum* L.) need 0.5-1 Lday^{-1}plant^{-1}, while cucumber (*Cucumis sativus*) needs up to 3 Lday^{-1}plant^{-1}. Table 6 shows that tank size increased with the increased water consumption rate of the cultivated plants. All parameters related to water uptake rates such as humidity, wind speed, energy source, and water availability were considered constant. Srivastava (1996) also reported tank size variation based on crop-related parameters. Spray frequency is another factor in tank size selection. Three types of spray frequency were considered: short spray time with a short interval (30-s on and 60-s off) (Pagliarulo and Hayden, 2000), short spray time with a long interval (10-s on and 7-min off) (Cho *et al*., 2017), and long spray time with a long interval (15-min on and 15-min off) (Lira *et al*., 2015). Table 6 also shows tank size differences based on spray fre-quency. A small tank was required for a short spray time with a long interval, while a short spray time with a short interval and a long spray time with a long interval both required a bigger tank. A short spray time with a short interval was suggested by Pagliarulo and Hayden (2000) for better plant growth in an aeroponic cultivation system. The gradual changes in the number of plant beds, tanks size, pipe diameter, and pumps capacity (flow rate and pressure) based on different parameters have been shown in Tables 5 and 6. Usually, the pump flow rate decreases with an increasing pressure head. In the simulation, the required pump size was chosen based on the required flow rate with the relevant pressure head.

Table 5. Calculated pump, pipe, and tank sizes based on the number of plants for the plant factory studied (assuming 25 plants on 1 plant bed).

No. of plant	No. of bed	Mixed nutrients supply subsystem				Stock nutrients supply subsystem						
		Tank for mixed nut. (L)	Pipe dia. (mm)	Irrigation pump Flow rate (Lmin^{-1})	Irrigation pump Pressure (kPa)	Target conc. (ppm)	Stock conc. (ppm)	Tank for stock sol. (L)	Tank for distilled water (L)	Pipe dia. (mm)	Nutrient pump Flow rate (Lmin^{-1})	Nutrient pump Pressure (kPa)
25	1	35	12	1.11	900	200	3000	3	35	6	1.5	100
50	2	70	12	3.38	700			5	70	6	3	100
100	4	140	12	4.86	300			10	140	6	3	100
200	8	280	12	5.46	156			20	280	6	3	100
300	13	455	19	28	1100			30	455	6	3	100
400	17	595	19	34	1000			40	595	6	3	100
500	21	735	19	37	900			50	735	6	5	100
750	31	1085	19	45	700			73	1085	6	5	100
1000	42	1470	19	47	600			100	1470	12	10	100
1500	63	2205	19	46	600			150	2205	12	10	100

Table 6. Calculated tank sizes variation based on plant species and spray frequency for each plant bed and daily basis.

Types of tank	Plant species			Spray frequency		
	Leafy vegetables (L)	Tomato/ Potato/ Pepper (L)	Cucumber/ Melon (L)	Short spray, short interval (L)	Short spray, long interval (L)	Long spray, long interval (L)
Nutrient mixing	34.27 ≈ 55	79.63 ≈ 80	230.83 ≈ 230	22.2 ≈ 25	2.2 ≈ 3	33.3 ≈ 35
Stock solution	2.33 ≈ 2.5	5.30 ≈ 5.5	15.39 ≈ 15.5	1.67 ≈ 2	0.2 ≈ 0.5	2.33 ≈ 2.5
Distilled water	32.5 ≈ 35	74.50 ≈ 75	214.5 ≈ 215	23.33 ≈ 25	2.8 ≈ 3	32.5 ≈ 35

Here, 0-200 plants could be irrigated using one high pressure–low flow rate pump, and 200-1500 plants could be irrigated using another high pressure–high flow rate pump, with little variation in flow rate and pressure head. It is also known that the diameter of the pipe depends on the flow volume and pressure head drops due to pipe friction. The calculated pipe friction for each plant bed was 6.20 kPa. If a high-pressure pump is used to cover 63 plant beds (1500 plants), the total friction loss would be 390.60 kPa. This would severely reduce the flow rate, resulting in interference with plant growth and death. To maintain a good flow rate and increase irrigation efficiency, several small pumps (unit basis) need to be used instead of a single large pump. Srivastava (1996) also suggested irrigation on a unit basis for water circulation optimization. Figure 5 shows a proportional relationship among tank size, the number of spay nozzles and plant beds. Increasing the number of plants requires more plant beds and consumes more water, resulting in more spray nozzles and a bigger storage tank. The size of the nutrient mixing tank, the number of spray nozzles, and the number of plants are shown for 1-10 plant beds.

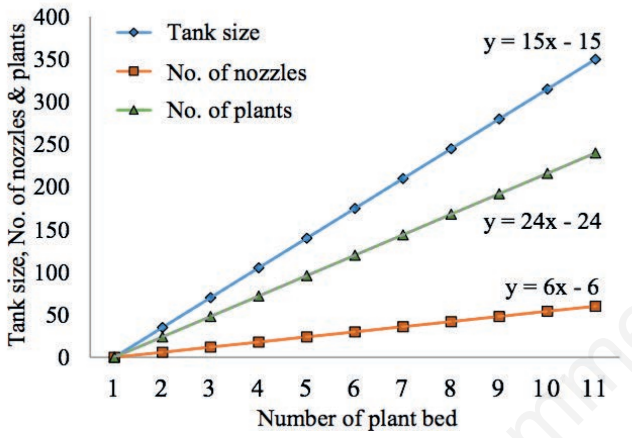

Figure 5. Relationship among tank size, no. of nozzles, plants and plant beds.

Application results of the suggested methods to the case study

A case study was conducted to demonstrate the procedure for pumps, pipes, and tank size selection. In the aeroponic nutrient management system studied, three plant beds were irrigated using one pump, and the relevant tank size was 60 L. After simulating the pump, pipe, and tank sizes, four plant beds could be irrigated using the same pump, keeping the nozzle pressure and flow rate the same, but considering the multi-objective method, the nutrient mixing tank size should be increased by 133% as shown in Table 7. Pump pressure, relevant flow rate, and number of irrigable plant beds, along with the number of cultivable plants are shown in Table 8. The validation results for pump pressure and flow rate are also shown. This table shows that the existing pump in the case study could provide 4.86 Lmin^{-1} at a pressure of 325 kPa to cover four plant beds without changing the nozzle pressure or droplet conditions.

To validate the calculated irrigation pump coverage, as shown in Table 8, the existing high pressure–low flow rate pump was tested. A flow meter and pressure gauge were attached to the pump outlet for measuring the pump flow rate and pressure head, respectively. The pump could provide a minimum of 2.30 Lmin^{-1} at 827.37 kPa and a maximum of 6 Lmin^{-1} at 101.33 kPa pressure head. It was run to cover one, two, three, four, and eight plant beds for 25, 50, 75, 100, and 200 plants, respectively. The simulated and measured pump flow rates and pressure heads for the respective number of plant beds were plotted for cross checking.

The Nash-Sutcliffe efficiency coefficient (NSE) was determined along with conducting a regression analysis between the simulated and observed flow rate and pump pressure data, as shown in Figure 6. For pump flow rate, NSE was 0.41 and R^2 was 0.98, with an intercept of 2.04 and a gradient of 1.28. Similarly, for pump pressure, NSE was 0.78 and R^2 was 0.99, with an intercept of 23.36 and a gradient of 0.85.Validation test results could be acceptable as those are higher than the satisfactory value (0.5) of

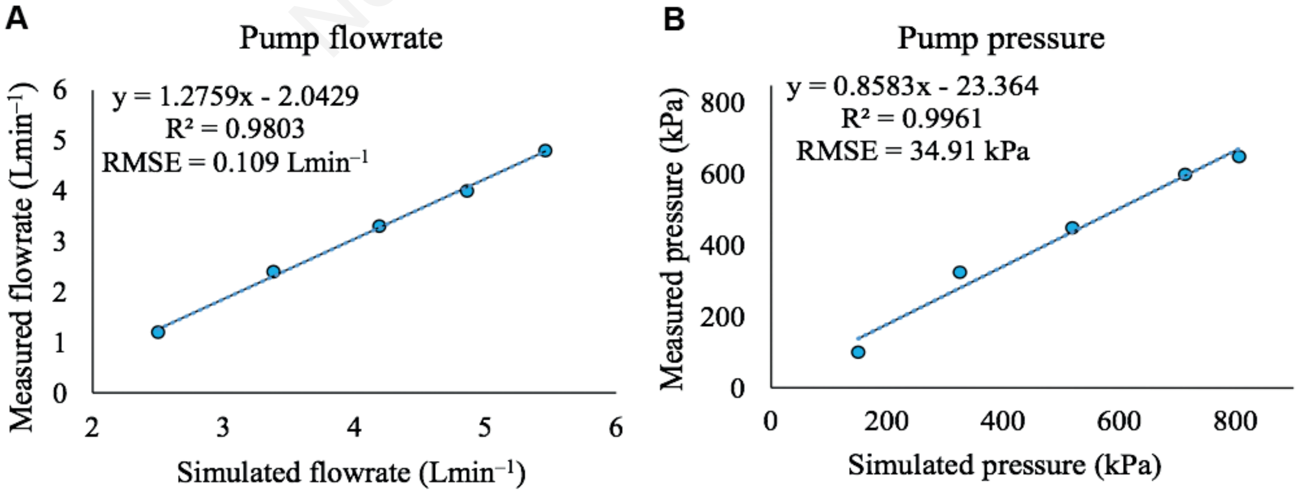

Figure 6. Regression between the calculated and measured flow rate (A), and pressure (B) data of the selected irrigation pump from the case study (No. of plant: 500, flow pressure: 300 kPa).

Table 7. Summary of the case study.

Parameters	Before study	After study	Notes
Irrigable plant bed	Three beds/one pump	Four beds/one pump	Irrigation coverage efficiency increased by 33%.
Pipe	-	-	The diameter of the pipe remained the same due to unit basis consideration.
Volume of tank	60 L for three beds	140 L for four beds	The volume of the nutrient mixing tank increased by 133% considering the multi-objective method.

Table 8. Calculated pump sizes based on nozzle pressure and flowrate.

Nozzle Pressure (kPa)	Nozzle Flowrate (Lmin^{-1} bed^{-1})	Calculated pump capacity (without pipe loss)		No. of irrigable bed	Calculated pump capacity (with pipe loss)		Validation test result for pump		No. of plants	Error	
		Pressure (kPa)	Flowrate (Lmin^{-1})		Pressure (kPa)	Flowrate (Lmin^{-1})	Pressure (kPa)	Flowrate (Lmin^{-1})		Pressure (kPa)	Flowrate (Lmin^{-1})
100	0.64	100	5.63	8	150	5.46	100	4.8	200	-33.33	-12.09
200	0.91	200	5.25	6	231	5.19	-	-	150	-	-
300	1.11	300	4.93	4	325	4.86	325	4.0	100	0	-17.70
400	1.28	400	4.44	3	419	4.58	-	-	75	-	-
500	1.43	500	4.25	3	519	4.19	450	3.3	75	-13.29	16.39
600	1.57	600	3.93	2	613	3.88	-	-	50	-	-
700	1.69	700	3.50	2	713	3.38	600	2.4	50	-15.85	-28.99
800	1.81	800	2.56	1	806	2.50	650	1.2	25	-19.35	-52.00
900	1.93	900	1.29	0	0	0	0	0	0	0	0

NSE and R^2 (Krause *et al.*, 2005; Golmohammadi *et al.*, 2014). Additionally, the root-mean-square error (RMSE) values were 0.109 Lmin^{-1} and 34.91 kPa for pump flow rate and pressure, respectively. The high RMSE value for pump pressure was caused by the small number of samples with high error predictions.

Conclusions

This study suggested a scientific approach targeted to improve the usual size selection procedures of pumps, pipes, and tanks for aeroponic nutrient management systems. Basic hydraulic principles were followed such as flow rate formula, Bernoulli's equation was used for pump size selection, the optimum pipe size was identified by calculating the velocity limit and friction factor values, and Washington State Department of Health's Water System Design Manual (2009) was followed for calculating the tank size. In the case study, the size selection methods were applied to an aeroponic system involving 500 plants. Calculation was also demonstrated to show the gradual changes in pump, pipe, and tank sizes based on the number of plants. The following conclusions were drawn from this study: i) an irrigation pump capable of delivering 37 Lmin^{-1} at 900 kPa pressure head, and a nutrition pump capable of supplying 5 Lmin^{-1} at a 40 kPa pressure were required for the 21 plant beds in the case study. Using a large pump, several numbers of plant beds could be irrigated, but this would reduce the nozzle flow rate and the droplet size would turn from very fine to coarse; ii) based on pipe friction analysis, it was found that several small pumps (unit basis) needed to be used instead of a single large pump to maintain a good flow rate and irrigation efficiency; iii) for irrigating the 500 plants in the case study, 750, 40, and 685 L tanks for nutrient mixing, stock solutions, and distilled water were required. Tank size varied based on the water consumption and nutrient spray frequency of various cultivated crops. A proportional relationship was found among tank size, total number of nozzles, number of plant beds, and number of plants.

The size calculation procedure demonstrated in this study could provide useful information for ensuring the sustainability of hydroponic nutrient supply techniques in terms of management effectiveness and maximizing plants' root zone coverage. Different types of pump, nozzle positioning pattern, spray strategies, and crop water consumption in different plant growth stages will be considered in future research.

List of abbreviations

ADD	Average day demand (L)
atm	Atmosphere
C	Coefficient of retardation from pipe materials (140~150 for PVC)
C_S	Stock solution concentration (ppm)
C_T	Target concentration (ppm)
D	Pipe diameter (m)
d	Inside diameter of pipe (mm)
D_{BB}	Bed to bed vertical distance (m)
d_N	Diameter of nozzle (mm)
EC	Electrical conductivity
El	Elevation pressure (kPa)
f	Friction factor
F_f	Friction factor per 100 inches of pipe (kPa)
g	Acceleration due to gravity (9.81 ms^{-2})
H_B	Height of plant bed (m)
H_D	Dynamic head (m)
H_S	Static head (m)
ISEs	Ion-selective electrodes
L	Pipe length (m)
N_N	Total no. of nozzles
N_{PB}	Total number of plant beds
N_T	Total number of layers or tiers

P_{pump}	Pressure of pump (kPa)
$P_{fit.}$	Pipe fittings kPa)
$P_{fric.}$	Pipe friction (kPa)
PHD	Peak hourly demand (L)
P_{loss}	Pipe loss (kPa)
P_N	Working pressure at nozzle (kPa)
P_{RES}	Pressure on the surface of the water in the reservoir (m)
P_{RT}	Pressure on the surface of the water in the receiving tank (m)
Q	Flow rate (Lmin^{-1})
Q_N	Nozzle flow rate (Lmin^{-1})
Q_{Pump}	Pump flowrate (Lmin^{-1})
Qs	Sum of active supply source (Lmin^{-1})
t	Time assumed to supply the fluid (min)
V1	Volume of liquid (L)
v	Velocity (ms^{-1})
V_D	Dead volume (L)
V_{DWT}	Volume of distilled water tank (L)
V_E	Equalizing volume (L)
V_{FS}	Fire suppression volume (L)
V_{MT}	Volume of mixing tank (L)
V_O	Operating volume (L)
V_S	Standby volume (L)
V_{ST}	Volume of stock solution tank (L)

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