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The Design and Technical Performance of Two Aeroponic Systems in Ghana

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Abstract

Climate change and its associated variabilities is having major impacts on agricultural production across the globe. Sustainable production options that reduce the vulnerability of the food system to climate change impacts are being advocated for, with a lot of ongoing research in that direction. Aeroponics production, a soilless production system has been identified as a sustainable system that can produce food with less input (land per unit area, water, nutrient and energy). It also makes for an environmentally friendly production system. In areas of extreme soil degradation and limited land area and water, aeroponics have shown great advantages over geoponics and sustained production, thus improving on food security. The central and northern parts of Ghana where yams are predominantly grown, is challenged with access to fertile lands, rainfall variabilities and other associated threat such as pest and disease outbreaks and seasonal bush fires. The production of seed yam, which form about 25% of the production cost for yam cultivation is hampered by all these challenges. To abate these challenges and improve on the adaptation measures taken by farmers around the region, two aeroponic systems were developed in this research, to be used for the production of seed yams propagated from vine cuttings. Two designs were made: one power independent (the gravity-fed open loop system) and the other power dependent (pressurised close loop system). In the systems design, the following aspects were taken into consideration: selection of head control and emitter; design of laterals and pipe sizes (inlet and outlet pipes); and the selection of growth chamber and feed tank. Apart from the selection of the growth chamber and the design of laterals and outlet pipe, different design considerations were also taken into account for the gravity fed system. This included the selection of drip lines and emitter flow rate. Technical evaluation of the aeroponics systems were done to ascertain its effectiveness as a fertigation system based on the performance indicators for a sprinkler and drip irrigation system. Results from the technical evaluation gave a mister discharge for the power dependent system ranging from 59.00-60.5 kPa. The emitter flow rate, the equivalent evaluation parameter for the power independent system also ranges from 0.10-0.12 L/h. There was a linear correlation between the mister operating pressure, mister discharge and swath diameter for the power-dependent system. For a Christensen's Coefficient of Uniformity (CU) and Distribution Uniformity (DU) values of 97.52% and 96.16% respectively, the power dependent system can be said to be very efficient in its operations. The same could be said for the power independent system having a CU and DU of 94.49% and 90.80% respectively. These two developed systems have shown their capability to be adopted for u se in seed yam production to reduce some of the associated challenges, especially, access to land, water, seasonal bush fires and pest and disease outbreaks.

Keywords: aeroponics, climate change, closed looped systems, drip hydroponics, fertigation, gravity-fed, seed yam production

1. Introduction

Hydroponic and aeroponic cultivation has been used for research and crop production around the world in various forms and designs. The technology has advanced a great deal in the last 50 years and has become, possibly, the most intensive method of crop production in today's agricultural industry (Kumari & Kumar, 2019). Aeroponics is a system of hydroponics in which the roots of the plants are suspended in a closed chamber and nutrient solution is sprayed from below (Kuncoro et al., 2021). A distribution system of pipes, spray nozzles, a pump and timer distribute the spray from a nutrient solution storage tank. The chamber and misting system provide complete control of the root zone environment, including temperature, nutrient level, pH, humidity, misting frequency and duration and oxygen availability (Tessema et al., 2017).

Because of the easy access to the roots, aeroponics has been used as a research tool since the 1940s, with work done using vegetable crops in the 1970s and 1980s (Lakhiar et al., 2018). Plants often exhibit accelerated growth and maturation in aeroponic systems (Kuncoro et al., 2021). These qualities have made aeroponics a popular research tool for scientists studying root growth and plant nutrient uptake (Selvaraj et al., 2019; Mbiyu et al., 2018). With all the evolving advances in aeroponic and hydroponic systems, the technology has not been used much and adapted for research or production in Ghana. This may be due to the limited research done in the area and the limited knowledge people have in the use for aeroponics for crop production. Whilst researchers are advocating for its use in research and crop production in Ghana, the future depends on developing systems which are competitive in production costs, adaptable to use in our part of the world and energy use efficient.

Aeroponic production also enables intensive production when there is available capital to be invested in the technology (Richa et al., 2018). Agricultural intensification systems increase production with increased investments in technology whilst limiting or maintaining the land area put under production (Ali, 2017). The economic benefit of scale of aeroponic production systems are thus substantial in intensification farming.

Aeroponics systems have been used for crop propagation and research by several authors. Selvaraj et al. (2019) designed and analysed a low-cost aeroponic phenotyping system for storage root development using cassava as a test crop. Evaluation of the system revealed the adaptive responses of storage root initiation and corroborated that they are significantly enhanced by exogeneous auxin supply. Endale et al. (2021), designed and evaluated an aeroponic system to facilitate the estimation of crop transpiration rate as well as water and nutrient uptake of the plant in response to salinity stress at the root zone using tomato as test crop. Their research found that tomatoes grown in the aeroponic system were less sensitive to salinity. Kuncoro et al. (2021) also evaluated the effects of aeroponic root chamber conditioning on mini-tuber seed cultivation and found that a temperature range of 10 °C to 20 °C improved potato seed tuber yields.

A major requirement for aeroponics production is electrical energy. This requirement thus limits its use to farms that can have access to electricity or other energy sources for its operation. Several systems are also seen as complex and hence its adoption for use is deterred by lack of expertise and technical knowhow for its operation. With these challenges in mind, this work sought to develop two simple low cost aeroponics systems, with one entirely power independent system to surpass these particular challenges. Two aeroponic systems were developed for use in the production of disease-free seed yams by the Council for Scientific and Industrial Research - Crops Research Institute (CSIR-CRI) and the Department of Agricultural and Biosystems Engineering of the Kwame Nkrumah University of Science and Technology (KNUST). Since a big part of the question of aeroponics technology's feasibility is energy cost, the overall objective of this work was to design one fully functional, low-cost pressurized (power dependent) aeroponic growth system and one fully functional low-cost drip (power independent) hydroponic system and evaluate their functionality as a fertigation system.

2. Method

The design and fabrication processes including the systems design and design components, and the technical evaluation are discussed here. Technical evaluations of the systems were done as per the criteria for evaluating pressurized and gravity-fed drip irrigation systems.

The functional requirement of this aspect was to design two fully functional, low-cost aeroponic growth systems. These are power-dependent and power independent systems known hereof as the pressurized closed-loop aeroponic system (PCLAS) and the gravity-fed aeroponic system (GFAS) respectively.

2.1 System Design of the Power-Dependent Aeroponics System

This is a system that utilizes electricity in its operations. It uses a high-pressure pump (Figure 1a.) which is used to atomize the water through small orifice misters to create water droplets of 50 microns or less in diameter. Fertigation is automatically timed using irrigation timers at two minutes and thirty minutes off.

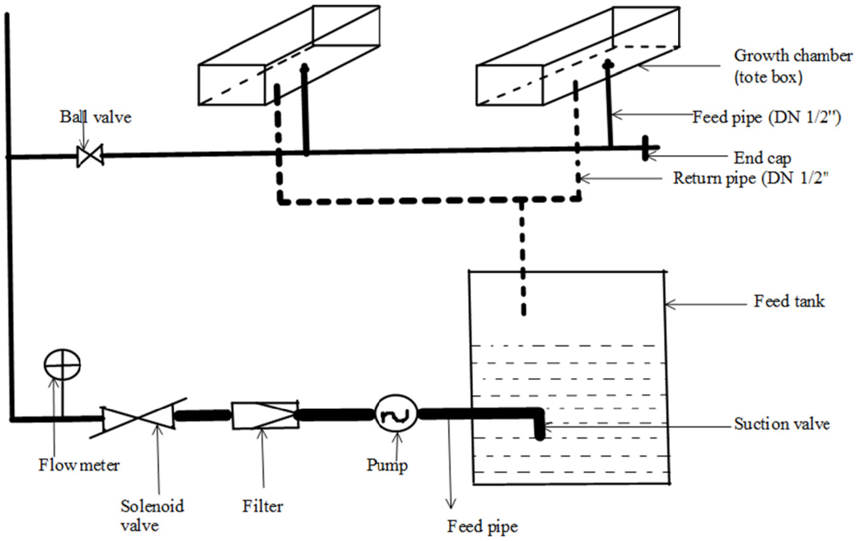

Figure 1a. Schematic representation of the pressurised system

2.1.1 Design and Selection of Mister

The diameter coverage and height of the growth chamber was considered or used in the selection of the emitter. Since a spray is required in irrigating/fertigating the roots, a single nozzle micro mister was selected. The number of misters (Figure 1b) per lateral was determined based on the number of growth chambers on the lateral. Each growth chamber was designed to have one emitter each base on the size (length, breath and height) of the growth chamber. Thus, each lateral had 3 misters each with mister operating pressure of 50 kPa at 1.5 m head and a swath diameter of 3 m.

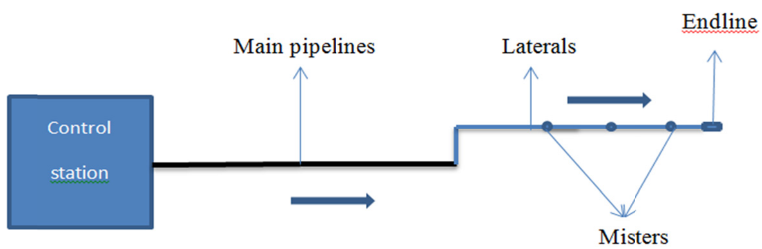

Figure 1b. System Flow Chart for one pressurised aeroponic unit

2.1.2 Pipelines and Lateral Design

The length of the lateral was designed based on the number and arrangement of the growth chamber. According to the split plot experimental design used for the agronomic evaluation, three yam varieties, grown in three different chambers, would be irrigated with the same nutrient solution at a particular time. Hence three tote boxes (growth chambers) were arranged horizontally (end to end) on a table. The total length of the three arranged boxes was taken. A length of 0.5 m was added to that of the three growth chambers to compensate for the inlet and end lines of the laterals. The total length of the three tote boxes was determined to be 1.5 m (with a length of 0.5 m for each). Compensating with the adjusted 0.5m length gave a total lateral length of 2.0 m.

The lateral flow rate was determined using the Equation 1 given by Phocaides (2000):

$$LFR = epl \times efl \tag{1}$$

where, *LFR* = Lateral flow rate; *epl* = emitters per lateral = 3; *efl* = emitter flow rate = 30 L/h.

Thus,

$$LFL = 3 \times 30\frac{l}{h} = 90\frac{l}{h}$$

The selection of pipe sizes was based on Equation 2 by Phocaides (2000).

$$q = kd \cdot H^{*} \tag{2}$$

where, q = emitter discharge; k and d are coefficients; H = pressure at the emitter and * is an exponent characterized by the emitter flow regime and the flow rate curve as a function of pressure.

The friction factor method (Equation 3) was used in sizing the laterals.

$$F_f = \frac{Po \times Pv}{Lc} \tag{3}$$

where, F_f = Allowable Psi loss per 100" of pipe; P_o = operating pressure of emitter; P_v = Allowable percentage pressure variance; L_c = longest run of lateral line (critical length).

Friction pressure loss was computed using the Equations 2-4.

$$H_f = [0.2083 \times \frac{100}{C}^{1.852} \times \frac{Q^{1.852}}{d^{4.866}} \times 0.433 \tag{4}$$

where, H_f = friction loss per 100'; c = coefficient of retardation based on pipe material; Q = Flow discharge; d = inside diameter.

The lateral friction loss was calculated using an irrigation calculation online based on Equation 3 and 4 (Washington State University, n.d.). For a 16 mm PVC pipe with 3 misters having a flow rate of 30 L/h (spaced 1 m apart), the frictional loss was estimated to be negligible by the calculator. Hence the 16 mm PVC pipe was chosen to be the ideal pipe size for the laterals.

According to Phocaides (2000) the main pipeline is selected in such sizes that the friction losses do not exceed approximately 15 per cent of the total dynamic head required at the beginning of the systems piped network. Phocaides (2000) further states that the flow velocity in the main pipeline should be kept below 1.7 m/s in (plastic tubes) and 2 m/s in other pipes (steel, aluminium etc). Since the main pipelines supplies directly to the laterals without branching a 25mm PVC a 25 mm PVC pipe chosen, based on the Equation 5.

$$V = Q/A \tag{5}$$

where, V = flow velocity; Q =discharge; A = Pipe cross-sectional area.

2.1.3 Head Control

The component parts of the system requirements. The system is complete with pump, filters, non-return valve, union joints and shut off valve. The total pressure head required for the system was designed based on Phocaides (2000) sum of the following pressures: pressure at the emitter, friction loss in the lateral line, friction loss in the valves and pipe fittings, differences in elevation and loss of pressure in head control. The brake horse power was determined using Equation 6 by Phocaides (2000):

$$BHP = (Q \times TDH)/(270 \times e_1 \times e_2) \tag{6}$$

where, Q = flow capacity in m^3/h; e_1 = Pump Efficiency; e_2 = Driving Efficiency; TDH = Total Dynamic Head; 270 = constant for metric units gives pump efficiency to range between 0.5-0.8.

Thus,

$$BHP = 90 \text{ L/h} \times \frac{3}{270} \times 0.7 \times 0.7 = 0.49$$

Hence a pump with a horse power of 0.5 was chosen. Since the 0.5 hp pump came with inlet and exit valves of 25 mm, 25 mm pipes and fittings were used in the design and installation of the laterals.

2.1.4 Design and Selection of Growth Chamber

The agronomic evaluation of this research sought to evaluate the growth and yield performance of three yam varieties propagated by the two systems. It therefore became imperative to design a system that can house each variety in a single unit whilst at the same time give room to irrigation with the same nutrient concentration.

Plastic tote boxes 0.5 × 0.4 × 0.3 m. in dimension and made locally in Ghana by Century Plastic Products Limited was chosen for the following reasons: made of plastic material that can withstand rot and infestation from constant contact with water and nutrients and its ability to be worked on (cutting and spraying). Once the pipe sizes to be used in the fertigation system was known, holes were punched through the sides (centrally) to pave way for the insertion of the pipes through the tote boxes (Figure 2a). Same was done beneath the tote boxes (Figure 2b) to allow for drainage.

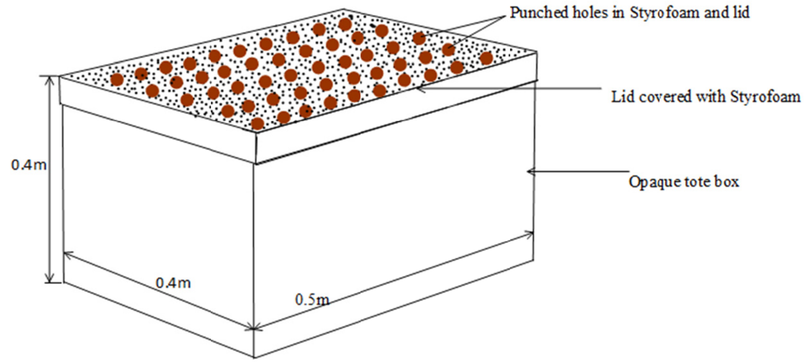

Figure 2a. Design specifications of the growth chamber and plant holding tray

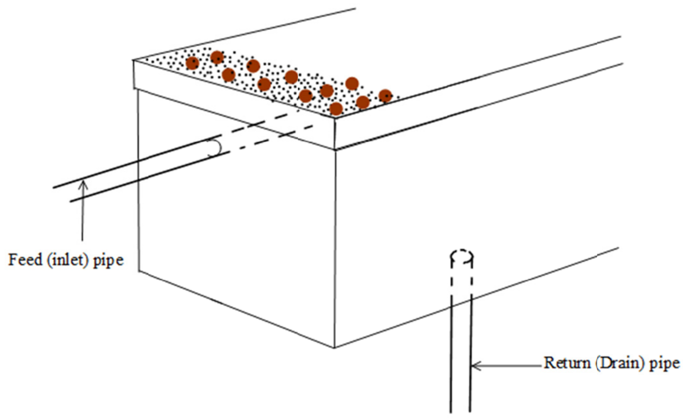

Figure 2b. Feed and return pipes of the growth chamber

2.1.5 Design and Selection of Feed Tank

Based on the design flow rate, a 150 m^3 feed tank was selected to hold the nutrient and water.

2.2 Systems Design of the Gravity-Fed Drip System

The gravity fed drip system, as the name implies, is non-power dependent. The nutrients are fed to the plants by gravity through pipes with drip emitters (Figure 3a). The feed tank is elevated at a height conducive for gravity flow (Figure 3b). An improvised drip emitter (Figure 3c) is made by punching micro holes spaced 6 cm apart on the 4 mm Polyethylene (PE) pipe for nutrient delivery to the base of the plant and subsequent flow to the roots.

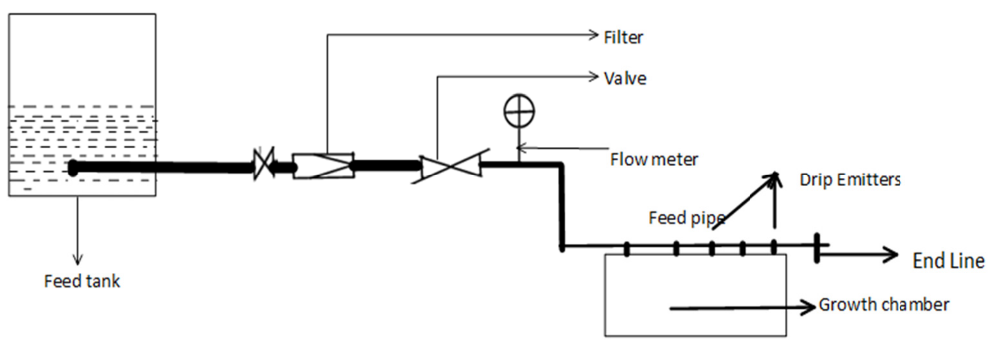

Figure 3a. Schematic representation of the gravity fed system

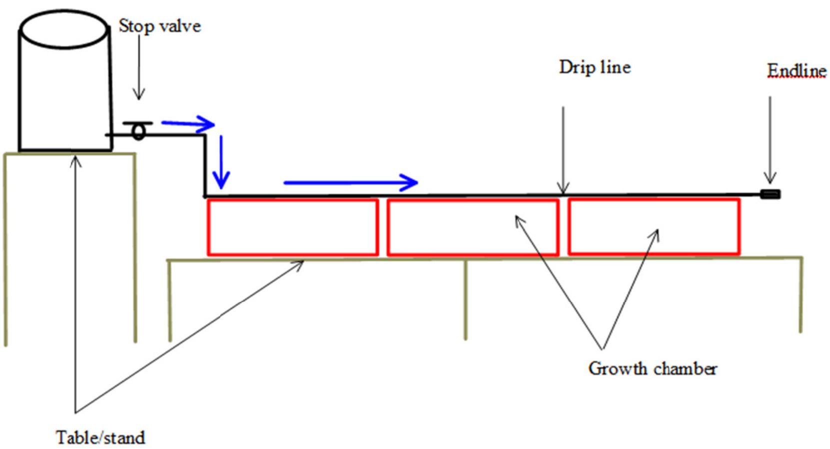

Figure 3b. System Flow Chart for the gravity-fed aeroponic unit

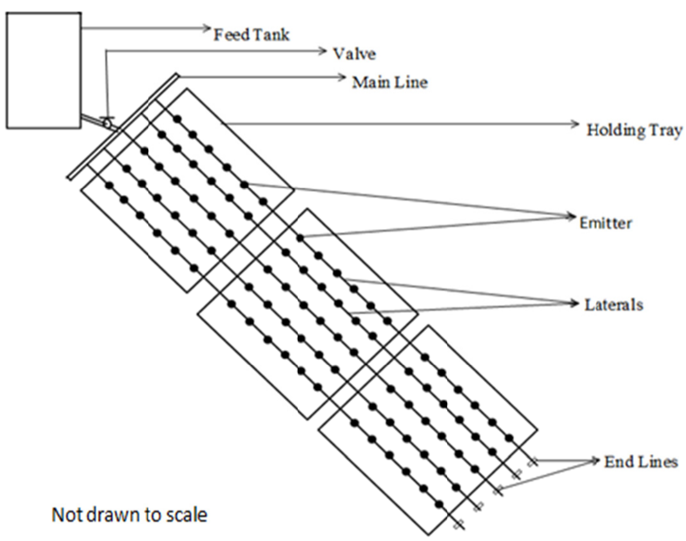

Figure 3c. Schematic representation showing laterals and emitters

2.2.1 Design and Selection of Laterals, Emitter Spacing and Flow Rate

Choosing emitters for aeroponics is more complicated than choosing it for soil applications. A lateral system relies on the soil to evenly spread water throughout the planting area.

2.3 Evaluating the Pressurized System

2.3.1 Measuring Mister Discharge

A 3 m length of a garden hose was connected to the nozzle of a mister and whilst the pump and mister were operating, the water was directed into a bucket over a 10-minute period. The volume collected into the bucket was measured with a measuring cylinder and recorded. The discharge was determined by dividing the volume collected by the time taken to collect the recorded volume. This procedure was repeated for the remaining misters to determine the individual discharges.

2.3.2 Measuring Mister Operating Pressure and Swath Diameter

The mister operating pressure was taken using a pitot tube connected to a pressure gauge. Each mister was also allowed to operate without being restricted by the growth chamber to determine the swath diameter. The misting head of a system can only distribute the water over a given area. The farthest distance covered by water droplets (throw) from the mister head's center line at which the mister deposits water in the growth chamber was measured. The swath radius was calculated as the distance from the center of the mister nozzle to one end of the wetted perimeter and multiplied by two to get the swath diameter.

2.3.3 Measuring Pump Operating Pressure

The pump operating pressure was measured using a pressure gauge connected to the discharge end of the pump. Data was taken and analyzed.

2.3.4 Determining Uniformity of Application and System Efficiency

Uniformity of application and irrigation efficiency is two performance measures used to evaluate an irrigation system. The two terms are used to describe the uniformity of application rate and the uniformity of coverage of sprinklers and emitters: these are mean application rate (MAR) and distribution uniformity (DU). The mean application rate (MAR) is defined as the average rate (in mm/h) that water is applied to the wetted area of the soil. Distribution uniformity is defined as a ratio of the smallest accumulated depths in the distribution to the average depths of the whole distribution (Lozano et al., 2020).

From the procedure used to determine the mister discharge, 25% of the catch cans with the lowest volumetric output was selected to form the lower quartile. The irrigation depth was determined by measuring the water in each catch can with a rain gauge calibrated in mm. The mean depth was determined by dividing the total of lower quartile catch depth by the number of catch cans forming the lower quartile. The uniformity of application was determined using Equation 7.

$$DU = \frac{\textit{Average lower quartile depth of application}}{\textit{Overall averarge depth of application}} \times 100\% \tag{7}$$

2.4 Evaluating the Gravity-Fed System

2.4.1 Determining Flow Rate of Perforated Emitters

To determine the discharge of perforated emitters, catch cans (Figure 4) were placed beneath each perforated position along the 2 m drip lines resulting in 90 catch cans for each distributing tank. The valve was opened and irrigation water was collected into the catch for an hour. Water collected from each can was poured into a calibrated measuring cylinder to get the volume of water in liters. The flow rate was calculated using Equation 8.

$$\text{Flow rate, } Q = \frac{V\,(\text{l})}{T\,(\text{h})} \tag{8}$$

Where, V is the volume of water collected in liters; and T is the time used in collecting the said volume.

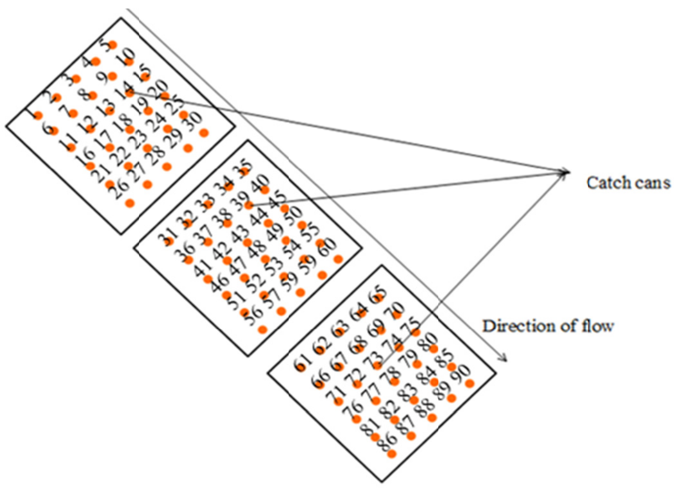

Figure 4. Grid view illustrating position of catch cans

2.4.2 Determining the Distribution Uniformity/Coefficient of Variation

If losses are low, and the volume of water flowing through the emitter is correct, the system can still be inefficient if the water is not applied evenly where it is needed. If the application is not even or uniform, some areas will get over-watered while some would not get enough. The uniformity coefficient was derived using the formula for the Christiansen's coefficient (CU) in Equation 9.

$$CU = (1 - \textstyle\sum_{k=0}^{n} \frac{x}{mn}) \times 100\% \tag{9}$$

where, Σx is the sum of the absolute deviations from the mean (mm or ml) of all the observations; m is the mean application depth measured (mm or ml); n is the number of observations (catch cans).

2.5 Data Analysis

Data collected from misters were further subjected to an analysis of variance using GenStat Version 11.0 data analysis software at 5% significance to determine if significant difference existed in interactions between operating pressure and swath diameter.

3. Results and Discussion

3.1 Power-Dependent System

3.1.1 Mister Discharge

The results from measuring the mister discharge are shown in Table 1. An S.E.D. of 3.72 and 0.39 for mister operating pressure and swath radius (respectively) is a good indication that there are no significant differences between the misters in terms of water delivered and the reach of the water delivered. Since swath diameter is a measure of the distribution of water and nutrients in the growth, significant differences between these interactions is suggestive that distribution in the box varies and thus not uniform. This could subject areas within the growth chamber to different treatments and thus introduce a higher variation with the chamber.

Table 1. Operating pressure and discharge of misters in the pressurised aeroponic

Mister Number	Mister Operating Pressure, kPa	Volume of Water Collected, L/30 min	Discharge, l/min	Swath diameter	Mister Number	Mister Operating Pressure, kPa	Volume of Water Collected, L/30 min	Discharge, L/min	Swath diameter
1	60	15.6	0.52	3	**20**	59.5	15	0.5	3
2	59.5	14.9	0.49	3	**21**	60	15.1	0.5	3.1
3	59.5	15.7	0.52	2.95	**22**	60	14.9	0.49	3.2
4	60	14.9	0.49	3	**23**	60	14.8	0.49	3.2
5	59	15.1	0.5	3	**24**	60	15.6	0.52	3.2
6	59	14.8	0.49	2.95	**25**	60	15	0.5	3.1
7	59.5	14.3	0.48	2.95	**26**	59.5	15.1	0.5	3
8	59	15.1	0.5	2.95	**27**	59.5	15.3	0.51	3
9	59.5	15.2	0.51	2.95	**28**	59.5	14.2	0.47	3
10	60	14.9	0.49	3.2	**29**	59.5	14.9	0.49	2.95
11	60	15.3	0.51	3.2	**30**	59.5	14.3	0.48	3
12	60	15.4	0.51	3.2	**31**	59.5	14.3	0.48	2.95
13	59.5	15.3	0.51	3	**32**	59.5	14.9	0.49	2.95
14	59.5	15.2	0.51	3	**33**	59.5	15.8	0.52	3
15	60	15.8	0.53	3.1	**34**	60.5	14.4	0.48	2.95
16	59.5	14.2	0.47	3	**35**	59.5	15.1	0.5	2.95
17	59	14.9	0.49	3	**36**	59.5	15.1	0.5	2.95
18	59.5	15.6	0.52	2.95	**Mean**	59.64		0.499	3.03
19	60	15.6	0.52	3	**SED**	3.724			0.39

3.1.2 Mister Operating Pressure and Swath Diameter

The manufacture's operating pressure for the mister was 50 kPa whereas the mean operating pressure of the misters was 59.64 kPa (Table 1). The misters were performing 19.28% higher than the manufacture's operating pressure. This can be attributed to the fact that the experimental design used demanded only three misters per pump whereas the pump operating pressure could be used for twice this number.

3.1.3 Uniformity of application

Using Christensen's coefficient of Uniformity (CU), and the Distribution uniformity, the uniformity of application of the power dependent system was determined to be 97.52% and 96.16% respectively. The CU obtained fell within the acceptable range for both high value crops CU > 84% and for general field and forage crops: CU > 75% (Jobbágy et al., 2021: Tomášik and Jobbágy, 2013). Prastowo, Hardjoamidjojo and Laelasari (2007) reported a CU of 91% - 97% during the evaluation of an aeroponic system and stated that the high CU values indicated that the nutrient solution flow along the laterals were relatively uniform in providing water, nutrients and air for the crop. Same can be said for this work. Again, the high distribution uniformity recorded could be attributed to the appropriate selection of the types of misters, mister spacing and efficient operating pressures of the pumps and misters. These high values could also be attributed to the fact that there were minimal frictional and leakage losses in the system resulting in a very low-pressure differential in the system (between the main pipelines and laterals).

3.2 Gravity-Fed System

3.2.1 Flow Rate of Perforated Pipes/Emitters

Emitter flow rates ranged from 0.10-0.12 L/h (Figure 6). The low level of variation in the system could be attributed to the pressure compensating effect given to the system. This was done by tilting the tables holding the growth chambers and the drippers at a 0.1% slope away from the fertigation tanks. The emitter flow rates were thus compensated in pressure by the slope hence the uniformity or minimum variations in its values. This method is usually employed on drip irrigated fields to compensate for pressure differences of the fields (Wu et al., 2010; Smeal, 2007; Julius et al., n.d.). Usually, when non-pressure compensating emitters are used, the flow rate decreases as the pressure is reduced and hence to obtain the desired uniformity, shorter lateral lines are used (Antonio et al., 2021). Employing this method also resulted in an opposing slope in the drainage pipes, thus allowing for easy flow of nutrients and water through the pipes. The drainage pipes were also sloped at 0.1% for easy flow of fertigation water back to the collecting/drain tank. This technique was also used by Choudhury et al. (2020).

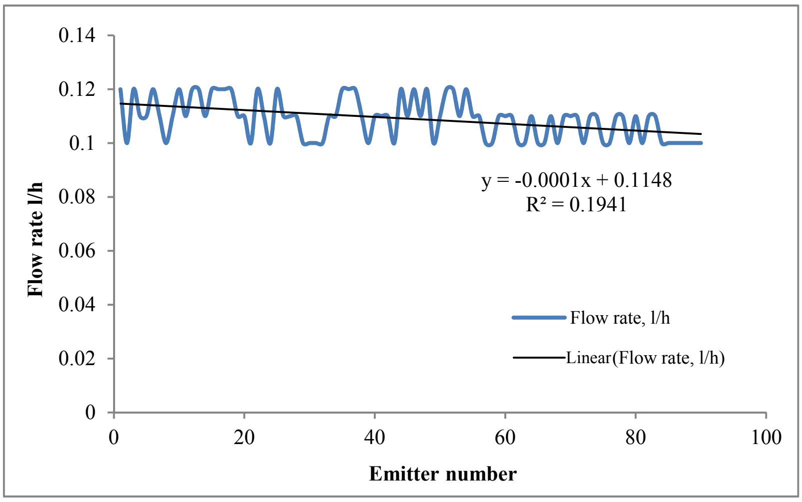

Figure 6. Emitter flow rate of the gravity-fed system

3.2.2 Distribution Uniformity/Coefficient of Variation

Gravity-fed systems are known for their inherent lower water pressures. If this is not well monitored, it can create variations in the emitter operation and water distribution. The method employed in ensuring a uniform flow rate also invariably affected the distribution uniformity of the system. A DU and CU of 90.80% and 94.49% respectively were attained from the evaluation of the gravity-fed system (Table 3). For micro sprinkler and drip systems, DU's of 90% are usually said to be ideal (Burt et al., 2000). Santos et al. (2013) reported uniformity coefficients above 80 and 90% for 25% flow rate variation, and classified this result as good and excellent respectively. Melo (2020) and Miranda et al (2018) also corroborates results found for CU in this work.

4. Conclusion

Two aeroponic systems were designed and evaluated for its technical efficiency to supply nutrient and water for the crop of interest, yam. The evaluation shows very good uniformity coefficient for both systems. Their performances are shown to be within acceptable design considerations for their efficient operation. The adoption of the simple power independent aeroponics system would allow for gains in the energy needed for operation of the system and subsequent decrease in operation cost. The power independent system also presents a parallel alternative to the power dependent system for remote off-grid producers. The simple design criteria used in this study can provide useful information for the development of aeroponic systems for other crops of interest.

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Appendix A

Parameters for calculating CU and DU

Emitter Number	Flow rate, L/h	Absolute Deviation	Emitter Number	Flow Rate, L/h	Absolute Deviation	Emitter Number	Flow rate, L/h	Absolute Deviation
1	0.12	0.011	31	0.10	0.009	61	0.11	0.001
2	0.10	0.009	32	0.10	0.009	62	0.10	0.009
3	0.12	0.011	33	0.11	0.001	63	0.10	0.009
4	0.11	0.001	34	0.11	0.001	64	0.11	0.001
5	0.11	0.001	35	0.12	0.011	65	0.10	0.009
6	0.12	0.011	36	0.12	0.011	66	0.10	0.009
7	0.11	0.001	37	0.12	0.011	67	0.11	0.001
8	0.10	0.009	38	0.11	0.001	68	0.10	0.009
9	0.11	0.001	39	0.10	0.009	69	0.11	0.001
10	0.12	0.011	40	0.11	0.001	70	0.11	0.001
11	0.11	0.001	41	0.11	0.001	71	0.11	0.001
12	0.12	0.011	42	0.11	0.001	72	0.10	0.009
13	0.12	0.011	43	0.10	0.009	73	0.11	0.001
14	0.11	0.001	44	0.12	0.011	74	0.11	0.001
15	0.12	0.011	45	0.11	0.001	75	0.10	0.009
16	0.12	0.011	46	0.12	0.011	76	0.10	0.009
17	0.12	0.011	47	0.11	0.001	77	0.11	0.001
18	0.12	0.011	48	0.12	0.011	78	0.11	0.001
19	0.11	0.001	49	0.10	0.009	79	0.10	0.009
20	0.11	0.001	50	0.11	0.001	80	0.11	0.001
21	0.10	0.009	51	0.12	0.011	81	0.10	0.009
22	0.12	0.011	52	0.12	0.011	82	0.11	0.001
23	0.11	0.001	53	0.11	0.001	83	0.11	0.001
24	0.10	0.009	54	0.12	0.011	84	0.10	0.009
25	0.12	0.011	55	0.11	0.001	85	0.10	0.009
26	0.11	0.001	56	0.11	0.001	86	0.10	0.009
27	0.11	0.001	57	0.10	0.009	87	0.10	0.009
28	0.11	0.001	58	0.10	0.009	88	0.10	0.009
29	0.10	0.009	59	0.11	0.001	89	0.10	0.009
30	0.10	0.009	60	0.11	0.001	90	0.10	0.009
Overall mean (m) = 0.109								

Equation 7: $DU = \frac{\text{Average lower quartile depth of application}}{\text{Overall averarge depth of application}} \times 100\%$

Using Equation 7, DU = 90.8%.

Equation 9: $CU = (1 - \sum_{k=0}^{n} \frac{x}{mn}) \times 100\%$

Using Equation 9, CU = 94.49%.

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