

Cloud-based Wireless Monitoring System and Control of a Smart Solar-Powered Aquaponics Greenhouse to Promote Sustainable Agriculture and Fishery in an Arid Region

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Abstract— This paper presents the design and implementation of an aquaponics greenhouse cloud-based wireless monitoring system and control that allow plants and fish to co-exist in a synergetic and controlled ecology. Two controllers are designed based on threshold values for effective nitrification and mineralization processes, as well as to enhance the rate of photosynthesis. As compared to our previous work, Wi-Fi technology and cloud data storage are utilized instead of GSM to reduce the cost in monitoring and increase accessibility of the aquaponics greenhouse parameters to many users. Modification in the design of the solar energy conversion system is done with higher ratings on solar panels and batteries to ensure an uninterrupted power. The experimental data gathered during summer and winter days in an arid region show the performance of the designed aquaponics greenhouse system in promoting sustainability. Current developments in the design and implementation of an aquaponics greenhouse system as well as possible improvements for large-scale production set-up are also discussed in the paper.

Keywords— agricultural engineering; aquaculture; hydroponics; automation; control design; electronic design, sustainable agriculture; sustainable fishery; renewable energy

I. INTRODUCTION

Countries in arid regions such as Middle East and African countries face several challenges in ensuring food security from agricultural sector due low fertility soil, limited irrigation water and adverse weather conditions in raising crops [1]-[4]. To promote growth in food production, improve quality of agricultural products, and increase in fish stock without over harvesting of marine food sources, scientific and technological researches on sustainable farming and fishing such as aquaponics, greenhouses and aquaculture are conducted and financially funded by government agencies and non-government institutions in arid regions [4]-[10].

An aquaponics greenhouse is a building structure for soil-less method of cultivating plants in hydroponic beds in conjunction with growing fish in aquaculture tanks. In a recirculating aquaponics system, fish excrete ammonia rich

wastes directly into the water of the aquaculture tanks [11]. As the water is being pumped into the hydroponic beds, the dissolved waste nutrients are converted by living bacteria into organic fertilizers needed for plant growth. In return, the plant roots filters and clean the water for fish utilization as it is recycled back into the aquaculture tanks [12]. To guarantee growth and survival of living organisms in an aquaponics greenhouse system, water quality parameters on the recirculating aquaponics system such as water temperature, pH, dissolve oxygen (DO), electrical conductivity (EC), total dissolve solids (TDS), total suspended solids (TSS), salinity, nitrate (NO_3), ammonia (NH_3) levels, as well as the greenhouse environmental parameters such as air temperature, relative humidity (%RH), carbon dioxide (CO_2) and lighting, must be monitored in real-time and automatically controlled [7],[8],[13],[14]. With this process, aquaponics greenhouse allows plants and fish to exist together in a synergetic and controlled ecology that promotes sustainability in agriculture and fishery [8]-[10],[12].

With this aquaponics greenhouse system, farming techniques and engineering methods that protect the environment, benefit the public health and support the local economy in arid region are applied to produce fish and vegetables. This eco-friendly system utilizes renewable energy source in terms of solar energy, water recycling and waste management [7]-[9],[12]. The use of cheaper energy source, minimal water exchange, organic fertilizer from fish waste and natural biofilter reduce the operating cost of the aquaponics greenhouse system; hence, it is considered as a cost-effective system [11],[12]. The growth in sales of the aquaponics greenhouse products support the economy of local communities [12]. Moreover, the harvested products from this system are organic, healthy and safe for human consumption [7]-[9],[12].

In this paper, Section II cites the current developments in the design and implementation of an aquaponics greenhouse system. Section III describes the design, set-up and implementation of the aquaponics greenhouse cloud-based

wireless monitoring system and control. In Section IV, the experimental data taken during a typical summer and winter seasons in an arid region show the performance of the designed aquaponics greenhouse system in promoting sustainability. Lastly, Section VI concludes the present paper and identifies the possible improvements in the design of aquaponics greenhouse system for large-scale production.

II. CURRENT DEVELOPMENTS IN THE AQUAPONICS GREENHOUSE CONTROL AND MONITORING SYSTEM

The need to constantly monitor and automatically control the aquaponics and greenhouse parameters to achieve healthy fish and plant growth is extensively studied [7][8][15]-[20]. A.M Nagayo et al. [7],[8] designed and implemented a smart and energy-efficient aquaponics greenhouse system using Arduino microcontroller interfaced with various sensors, actuators, NI LabVIEW software and GSM shield to monitor and automatically control the necessary water quality parameters and greenhouse environmental conditions for Nile tilapia, water spinach and lettuce production with minimal operating cost and human intervention. The experimental data and analysis of results showed that the system was sustainable to be used in Oman and other arid regions. However, to reduce the cost in monitoring the system performance, the use of Wi-Fi technology and cloud data storage was recommended instead of GSM[8]. Also, the design of the solar power conversion module needs to be modified to ensure 24/7 operation of the whole system. M.F. Saaid et al [15] presented a design of automated indoor aquaponics using Arduino microcontroller that monitors and controls the temperatures in fish and plant areas, feeding of fish and water level in the aquaculture tank.

D. Karimanzira, et al. [16] demonstrated the use of dynamic modelling technique to analyse aquaponics system to produce Nile tilapia and tomatoes. The designed INAPRO system is a double recirculation system consisting of recirculating aquaculture system (RAS) and recirculating hydroponics unit within a greenhouse. For management and control of aquaponics system, it uses dynamic two player systems associating two controllers – RAS and greenhouse controllers [16]. This model was implemented in VBA Excel to simulate various aquaponics conditions for possible large-scale production in the future.

Ipanera, an Industry 4.0 based architecture for aquaponics system was published by P.C.P. De Silva and P.C.A. De Silva [17] to control water quality parameters using adaptive fuzzy controller. This Internet of Things (IoT) system requires two control operations: (a) control for the effective mineralization of fish waste to fertilizer and (b) a process control for supervisory monitoring [17]. Ipanera consists of the following modules: (a) endpoints which are responsible for gathering data and control all the operations of a soil-less food production system using fuzzy logic; (b) IoT cluster that provides a platform for registering and grouping endpoints, setting-up communication from one endpoint to another, generating alerts to endpoints and updating fuzzy

configuration; (c) analytics server which conducts parameter optimization of the individual fuzzy controllers, analysis of data from all endpoints and predictions as well as machine learning operations; and (d) Hypertext Transfer Protocol (HTTP) server that stores the modified controller updates [17]. Another fuzzy logic controller for aquaponics system prototype was designed and implemented by F.J. Baldonado which automates the process of maintaining the temperature, pH and water levels to ensure for fish and plants growth [18]. However, this system monitors and controls only limited water quality parameters.

D. Wang et al. designed a smart monitoring and control for aquaponics system based on OpenWrt [19]. The system consists of the following modules: (a) sensor data acquisition module that gather real-time environmental parameters such as temperature, humidity, water level, oxygen in water, E-coli level and photos; (b) control and management center, consisting of Arduino and WRTnode, which stores the data collected, process data, upload data to the Web server and download the instruction information from the server to execute controlled operation; (c) Web server that stores and analyze the information from the sensor and camera [19]. With the designed system, the user or farm owner, can use mobile terminal to monitor and activate the actuators such as air pump, water pump and lamp remotely. On the other hand, a proposed system for an autonomous aquaponics system using 6LoWPAN based Wireless Sensor Network (WSN) and Next-Generation Telco was presented by N. Hari Kumar et al. [20]. The proposed system consists of WSN devices, temperature/pH/nitrate sensors, cloud data storage, trend analysis module for predicting the future values of Nitrate and PH, and image analysis module to classify healthy fish from disease- infected fish [20].

III. AQUAPONIC GREENHOUSE SYSTEM DESIGN CONSIDERATIONS

A. Block Diagram of the Aquaponics Greenhouse Control and Monitoring System

Fig. 1 shows the modified block diagram of the Aquaponics Greenhouse Control and Monitoring system based on the recommendations given by A. M. Nagayo et al. [8]. The modified system consists of two microcontrollers. Controller 1 (C1) is an Arduino microcontroller that controls water quality parameters of the aquaculture tank and hydroponic beds for effective nitrification and mineralization process. Controller 2 (C2) is a Particle Photon microcontroller which controls the greenhouse environmental parameters to improve the rate of photosynthesis in the hydroponic bed. Both microcontrollers perform the following tasks: (a) read and process data from various sensors through signal conditioning circuits; (b) verifies the data gathered with the defined threshold values, and (c) triggers the actuators when the sensor readings are not within the normal limits to perform a controlled operation. The actuators such as water pumps, aeration pumps, greenhouse lights, warmer lamps, exhaust fans, evaporative cooler and DC motor for fish feeder are turned on

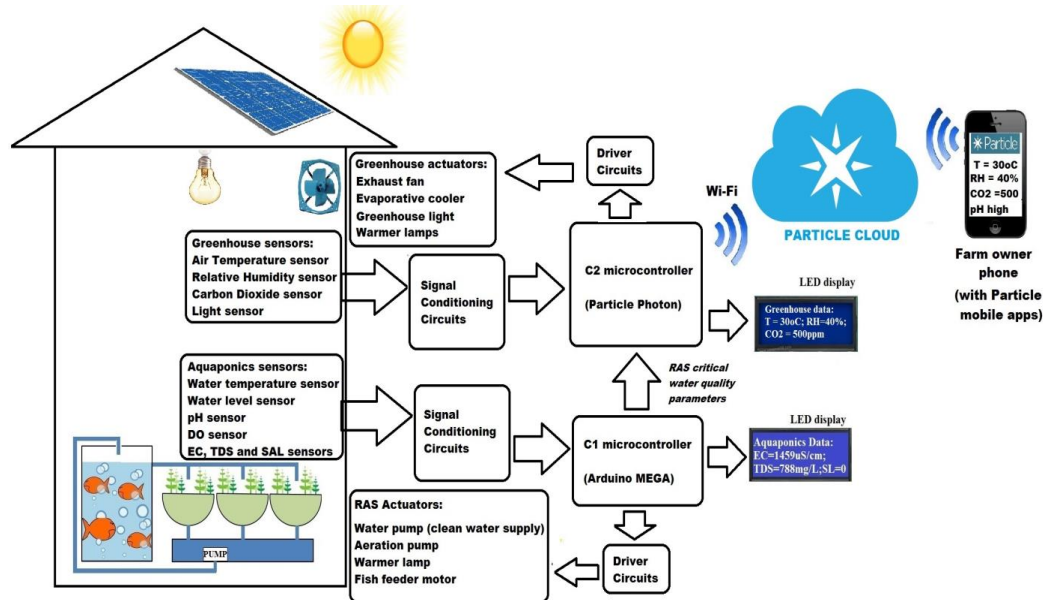


Fig. 1. Block diagram of the aquaponics greenhouse control and monitoring system.

by the microcontrollers through driver circuits. For monitoring purposes, the real-time data gathered by the Arduino and Particle Photon microcontrollers are displayed in LCDs. Also, greenhouse environmental parameters and critical water quality parameters in the Recirculating Aquaponics System (RAS) are published in the Particle Cloud, which can be accessed by farm owner anytime using the Particle mobile application software. The completed Aquaponics Greenhouse facility located at the grounds of Al Musanna College of Technology, Oman is shown in Fig 2 and the set-up inside it.



Fig. 2. The actual aquaponics greenhouse facility and the set-up inside it - aquaculture tank, hydroponic beds, control and monitoring system

B. Control and Monitoring of Greenhouse Environmental Parameters

To improve the rate of photosynthesis and other plant growth processes in the hydroponic beds, greenhouse environmental parameters such as air temperature (T_{air}), relative humidity (RH), carbon dioxide (CO_2) level and light intensity, are controlled and monitored automatically [7],[8]. The C2 controller was designed based on threshold values for each sensor specified by [7],[8],[21]-[28] that allow the optimal growth of water spinach (*Ipomoea aquatica*) in the hydroponic beds during summer season, with the addition of lettuce (*Lactuca sativa*) in winter season. Table I shows the set range of threshold values for the greenhouse environmental parameters, which are monitored remotely by the farm owner using the Particle Cloud mobile apps, and controlled operation to be done through actuators when the parameter values are out of range.

C. Control and Monitoring of Water Quality Parameters in the Recirculating Aquaponics System (RAS)

To allow the optimum growth of tilapia (*Oreochromis niloticus*) in the aquaculture tank and the water spinach (*Ipomoea aquatica*) in the hydroponic beds in summer time, with addition of lettuce (*Lactuca sativa*) during winter time, water quality parameters of the aquaponics system such as water temperature (T_{water}), pH level, dissolved oxygen (DO) level, electrical conductivity (EC), total dissolve solids (TDS) and salinity (SAL), are controlled and monitored automatically [7],[8]. The C1 controller was designed based on threshold values for each sensor specified by

TABLE I. RANGE OF THRESHOLD VALUES FOR THE GREENHOUSE ENVIRONMENTAL PARAMETERS AND THE CORRESPONDING CONTROLLED OPERATIONS

Greenhouse Environmental Parameters	Sensor Used	Acceptable Range of Values	Set threshold values based on A.M Nagayo et al. [7],[8]	Controlled operation based on A.M.Nagayo et al. [7],[8]
Air Temperature (T_{air})	DHT22	17 °C to 30 °C [24]	17 °C to 30 °C	If $T_{air} \leq 16^{\circ}\text{C}$, warmer lamps (W) are turned ON. If $T_{air} > 30^{\circ}\text{C}$, exhaust fan (F) is turned ON. If $T_{air} > 33^{\circ}\text{C}$, evaporative cooler (E) is turned ON. If $T_{air} < 10^{\circ}\text{C}$ or $T_{air} > 40^{\circ}\text{C}$, publish critical parameters in Particle Cloud.
Relative humidity (RH)	DHT22	25% to 70% [22]	40% to 70%	If RH > 70%, exhaust fan (F) is turned ON. If RH < 40 %, evaporative cooler (E) is turned ON. If RH < 25% or RH > 85%, publish critical parameters in Particle Cloud.
Carbon Dioxide (CO_2)	MG811	340 ppm to 1300 ppm [25],[26]	340 ppm to 1300 ppm	If $\text{CO}_2 > 1300\text{ppm}$, exhaust fan (F) is turned ON. If $\text{CO}_2 < 340\text{ppm}$, warmer lamps (W) is turned ON since heating can increase the amount of carbon dioxide in the greenhouse [27]. If $\text{CO}_2 < 200\text{ ppm}$ or $\text{CO}_2 > 1800\text{ ppm}$, publish critical parameter in Particlae Cloud.
Light Intensity	Light Dependent Resistor (LDR)	LDR $V_{out} < 4\text{ V}$ [7],[8]	$V_{out} < 4\text{ V}$	If the output voltage of the LDR circuit, $V_{out} \geq 4\text{ V}$ (dark room), greenhouse lights are turned ON. This greenhouse light (G) will act as an artificial light during nighttime to enhance plant growth and development [28].

[7],[8],[24],[29]-[34] to maintain good water conditions for plants and fish. Table II shows the set range of threshold values for the water quality parameters, which are monitored remotely by the farm owner using the Particle Cloud mobile apps, and controlled operation to be performed through actuators when the parameter values are not within the desired limits.

D. Cooling and Heating System of the Aquaponics Greenhouse

In regions with extremely dry climates, like Middle East and some African countries, evaporative cooling of air has the added benefit of conditioning the air with more moisture [8]. For the aquaponic greenhouse facility, a pad and fan type evaporative cooler shown in Fig. 3 is used to lower the air temperature and increase the relative humidity inside the greenhouse through the evaporation of water [7],[8]. Aside from evaporative cooler, exhaust fan is installed on the top wall of the greenhouse to vent out the accumulated hot air.

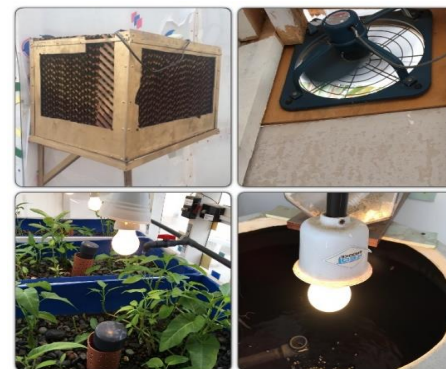


Fig. 3. Cooling and heating system of the aquaponics greenhouse [7],[8].

TABLE II. RANGE OF THRESHOLD VALUES FOR THE RAS WATER QUALITY PARAMETERS AND THE CORRESPONDING CONTROLLED OPERATIONS

Water Quality Parameters	Sensor Used	Acceptable Range of Values	Set threshold values based on A.M Nagayo et al. [7],[8]	Controlled operation based on A.M.Nagayo et al. [7],[8]
Water Temperature (T_{water})	D18B20 temperature sensor	16 °C to 33 °C [7],[8],[24]	16 °C to 33 °C	If $T_{\text{water}} > 33^{\circ}\text{C}$, water pump (WP) is turned ON for 25% partial water replacement.
				If $T_{\text{water}} < 16^{\circ}\text{C}$, warmer lamps (W) are turned ON.
				$T_{\text{water}} < 12^{\circ}\text{C}$ and $T_{\text{water}} > 35^{\circ}\text{C}$, the critical parameter is published in the Particle Cloud.
pH level	Atlas Scientific pH sensor	For plant, pH ≥ 5.5 to pH ≤ 7.5 [24]	5.5 to 8.0 ppm	If pH < 5.5 or pH > 8.0 , water pump (WP) is turned ON for 25% partial water replacement, and the critical parameter is published in the Particle Cloud.
		For fish, pH ≥ 5.5 to pH ≤ 10.0 [31]		
Dissolved Oxygen (DO) level	Atlas Scientific DO sensor	For fish, DO > 5.0 to DO $\leq 11.5\text{mg/L}$ [30]	DO ≥ 5.0 to DO $\leq 11.5\text{ mg/L}$	If DO < 5.0 , aeration pump (AP) is turned ON to increase the oxygen level.
		For plant, DO $> 3.0\text{ mg/L}$ [24]		If DO < 5.0 or DO > 11.5 , water pump (WP) is turned ON for 25% partial water replacement, and the critical parameter is published in the Particle Cloud.
Electrical Conductivity (EC) , Total Dissolved Solids (TDS) and Salinity (SAL) levels	Atlas Scientific Conductivity K 1.0 sensor	EC ≥ 30 to EC $\leq 5,000\text{ uS/cm}$ [31]	EC ≥ 30 to EC $\leq 5,000\text{ uS/cm}$	If one of the parameters is not within the set range, the water pump (WP) is turned ON for 25% partial water replacement, and the critical parameter is published in the Particle Cloud.
		Acceptable TDS value is about half of EC [31].	TDS $\leq 2,500\text{ mg/L}$	
		SAL ≥ 0 to SAL $\leq 2.0\text{ ppt}$ [34]	SAL ≥ 0 to SAL $\leq 2.0\text{ ppt}$	

During daytime, the heat requirement of the greenhouse is provided by the sun. However, at cold winter nights, warmer lamps shown in Fig. 3 act as heat sources which increase the air temperature more than a few degrees above the outside air temperature [7],[8],[35].

E. Solar Energy Conversion System

Based on the recommendation of A.M. Nagayo et al. [8], solar panels and batteries with higher ratings are required to ensure that the aquaponic greenhouse system is powered-up reliably for 24 hours a day and 7 days a week. During peak summer season, the evaporative cooler, exhaust fan and water pumps are activated and operating most of the time. With these conditions, the AC power requirement of the aquaponics greenhouse system is computed as 370 Watts and the total

energy requirement per day after correction factor is 7265.5 Watt-hours. Considering the calculated solar energy needed daily, four (4) 300 W, 28 V PV panels and eight (8) 12V, 200 Ah deep-cycle batteries are utilized, which are designed to be discharged at 25% to prolong the life of the batteries. A PWM solar charge controller with a rating of 60 A, 24 V is utilized, since it matches the ratings of the batteries in series-parallel connection. An inverter of 1000 W with 24 V DC input and 220 Vrms AC output, is used for the system, since the inverter power rating should be normally 25% to 30% greater than total watts (W) of appliances and DC input voltage should match the voltage of the battery bank. In providing DC regulated voltages of 12 V and 5 V to the sensors, signal conditioning circuits microcontrollers and driver circuits, switched mode power supplies are used.

IV. EXPERIMENTAL DATA AND ANALYSIS OF RESULTS FOR THE AQUAPONICS GREENHOUSE SYSTEM

A. Test Results of the Control and Monitoring System for the Greenhouse Environment

The sample greenhouse environmental parameters read by the sensors and status of the actuators taken on a typical winter time are shown in Fig. 4. The sample greenhouse data published in the Particle Cloud on a typical summer day are presented in Fig.5. Before performing the actual testing in the aquaponics greenhouse facility, the temperature readings of DHT22 were calibrated with digital and analog thermometers, and its relative humidity readings were calibrated with a psychrometer. As for the carbon dioxide (CO₂) sensor readings, the data were correlated with the MG811 sensitivity curve, temperature and relative humidity characteristics as specified on the manufacturer's data sheet [8]. Based on the experimental results, the greenhouse controller (C2) responded in well in accordance with the set threshold values.

As seen in Fig. 4, exhaust fan (F) was turned on since the relative humidity (RH) exceeded 70%. Fig. 5 shows that the air temperature inside the greenhouse increases while the relative humidity decreases during daytime in summer season, which matches with the typical weather condition in an arid region. Due to hot and dry weather during summer, the exhaust fan (F) and evaporative cooler (E) were activated most of the time to decrease the temperature in the greenhouse as compared to the outside temperature [8]. As seen in Fig. 6, the evaporative cooling system can lower the temperature inside the greenhouse by 2°C to 8°C and increase the relative humidity by 20% as compared to the outside environmental conditions. But, this cool air cannot be kept in the greenhouse due to effect of radiation and re-radiation of incident solar energy coming from the outside and diffused through the transparent walls [7],[8]. Referring to Fig.5, the carbon dioxide (CO₂) concentrations in the greenhouse during daytime decreases because the plants use carbon dioxide to carry on with the photosynthesis process [25]. At daytime, the LDR voltage readings are low due to exposure of greenhouse hydroponic beds to sunlight.



Fig. 4. Sample Aquaponics Greenhouse data and status of actuators taken on a typical winter day as displayed on an LCD

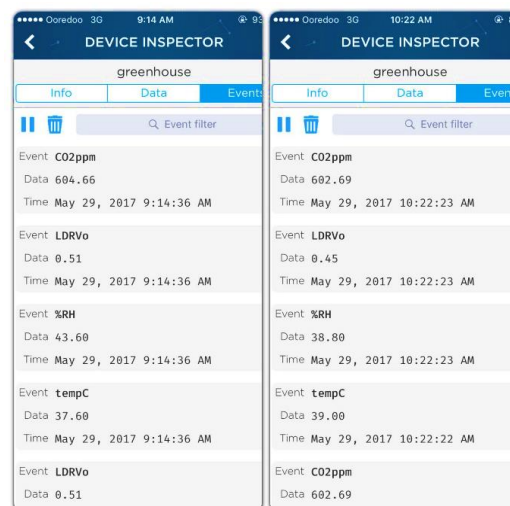


Fig. 5. Sample greenhouse data published in the Particle Cloud on a typical summer day

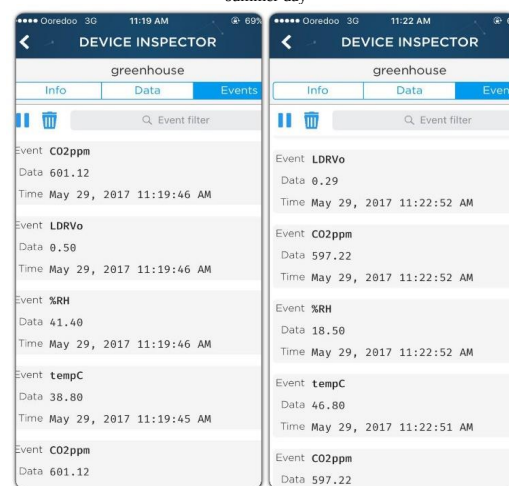


Fig. 6. Environmental parameters inside and outside the greenhouse on a typical summer day

B. Test Results of the Control and Monitoring System for the Recirculating Aquaculture System

Fig.4 and Fig.7 show the RAS water quality parameters read from the sensors and status of the actuators taken a typical summer and winter days respectively. Before dipping the pH, DO and conductivity K1.0 sensors in the aquaculture tank, they were calibrated properly using the chemical solutions provided by the manufacturer. The pH sensor readings were also verified with the result of the pH test strip

that was dipped into the aquaculture tank. Digital and analog thermometers were used to calibrate the D18B20 temperature sensor.

As seen in Fig. 4, water pump (WP) was turned on for 25% clean water replacement since the pH reading was below 5.5, and SMS = 1 means that critical alert message was published in the Particle Cloud. As seen in Fig. 7, the dissolved oxygen (DO) decreases as the water temperature increases due to the low solubility of oxygen when the temperature of water is high [8],[38]. As observed in Fig.7, the pH readings fluctuate due to photosynthesis and respiration by plants and vertebrates [39],[40]. During day time, CO₂ is absorbed by the plants from the water. With this condition, pH levels increased since there was less carbonic acid produced from chemical reaction of CO₂ and water [39],[40]. Moreover, significant changes in pH, electrical conductivity (EC), total dissolve solids (TDS) and salinity (SL) readings happened 2 hours after feeding the fish due to uneaten fish feed and production of fish waste [8],[37],[41]. These changes caused microcontroller C1 to enable the water pump (WP) for 25% clean water replacement and critical parameter alert was published in the Particle Cloud. Based on the experimental results, the RAS controller (C1) operated well in accordance with the set threshold values. Controller C1 activates the fish feeder system (FF) every 12 hours for a period of 30 seconds to release approximately 40 grams of commercial feed to the 14 Nile tilapia fish of 150g each in the aquaculture tank with a feeding rate of 4%.

With the modified solar energy conversion system design, the greenhouse aquaponics facility continuously operates for 24 hours even during summer season when evaporative cooler, exhaust fan and water pump are active all throughout the day.

IV. CONCLUSION

The current developments in the design and implementation of an aquaponics greenhouse system are presented in this paper with one common goal which is to ensure optimal growth and survival of plant and aquatic species in a synergetic and controlled ecosystem. This paper also discussed the design and implementation of a cloud-based wireless monitoring system and control for a solar-powered aquaponics greenhouse based on the recommendation by A.M Nagayo et.al [8]. Wi-Fi technology and cloud data storage are employed instead of GSM to lessen the cost in monitoring and increase accessibility of the aquaponics greenhouse parameters to farm owners and administrators. The design of the solar power conversion set-up that supplies electricity to the aquaponics greenhouse system was modified to ensure uninterrupted power for 24 hours a day and 7 days a week even when majority of the actuators are turned on. The experimental results obtained during summer and winter days showed that the designed aquaponics greenhouse system is suitable for implementation in arid regions to promote sustainability in agriculture and fishery.

For a large-scale production set-up of the designed aquaponic greenhouse in arid regions, the following may be done as future directives: (a) use of mechanical shading

mechanism and increase number of evaporative cooler and exhaust fan units to address the problem of high temperature and low relative humidity [8]; (b) utilization of nitrate sensor and ammonia sensor for detailed analysis of water quality parameters [8]; (c) use of fuzzy logic to optimize the control response [18], nitrification process [17] as well as power requirement; (d) employ image processing techniques for evaluating disease infected fish [20] and plants; (e) statistical modelling to predict the environmental and water quality parameters to enable farm owners and administrators to perform system maintenance before critical condition arises, and (f) business plan for implementing this project as a possible source of income for local communities [8].

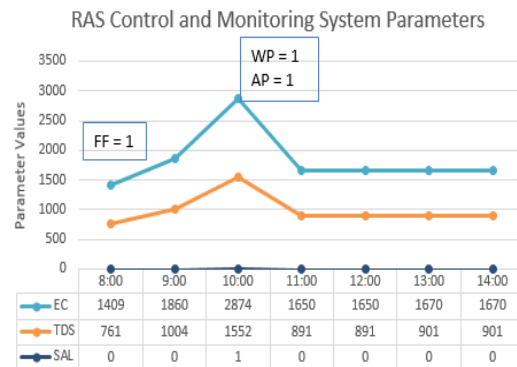
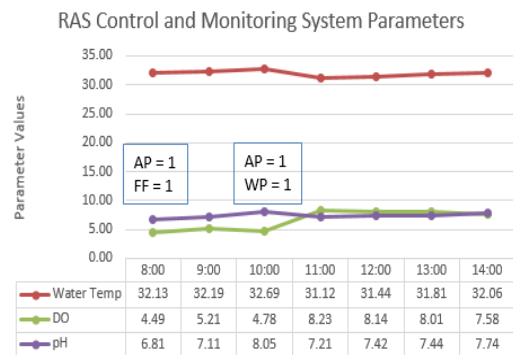


Fig. 7. Recirculating Aquaponic System data taken on a typical summer day

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