Research Article
Data Acquisition for Monitoring Vapor Pressure Deficit in a Tropical Lowland Shelter-house Plant Production

Ramin Shamshiri and Wan Ishak Wan Ismail
Department of Biological and Agricultural Engineering, Universiti Putra Malaysia,
43400, Serdang, Selangor, Malaysia

Abstract: The objective of this study was to monitor air Vapor Pressure Deficit (VPD) in a tropical lowland shelter-house plant production. A custom-designed real-time Data Acquisition (DAQ) system with three independent microcontroller boards and sensors for monitoring aerial parameters was developed, calibrated and tested. Sample temperature and Relative Humidity (RH) data for VPD calculations were continuously collected every 60 sec, for 6 days, inside a 40 m^2 shelter-house located at the Universiti Putra Malaysia agricultural experimental field. Preliminary results showed that VPD values varied from 0.16 to 2.51 kPa, with a mean of 0.83 kPa and standard deviation (Std) of 0.6 kPa. Different regression models were used to describe the nonlinear correlation that existed between temperature and VPD data. Results showed that squared polynomial model produced the maximum coefficient of determination (R^2) equal to 0.976. This model was successfully used for VPD prediction based on temperature inputs. The hypotheses that collected data follow normal distribution and have different means in the 6 days of experiment were rejected at any significant level. The result of this study can be used in decision support systems' database for controlling tropical lowland plant production environments.

Keywords: Data acquisition, microcontroller, plant production, relative humidity, shelter-house, temperature, tropical lowland Malaysia, vapor pressure deficit

INTRODUCTION

Controlled Environmental Plant Production Systems (CEPPS) with fully covered transparent material are widely used in Tropical Lowland (TL) regions; however the excess heat imposed by the direct solar radiation cause substantial amount of increase in the inside temperature and ambient Relative Humidity (RH). Ajwang and Tantau (2005) reported that under humid tropical climatic conditions, increase in temperature can rise to 38°C. In order to take into account both temperature and (RH) measurements, calculating the difference between the actual air moisture and its saturated point, denoted as Vapour Pressure Deficit (VPD), is of interest. Large values of VPD, (approximately higher than 2 kPa), cause high transpiration rates with significantly increases in Evapo Transpiration (ET) demands (El-Sharkawy et al., 1986) and stomatal closure (Pettigrew et al., 1990). Plants transpiration may be suppressed at low VPD which impacts the energy balance of the canopy. According to Pregner and Ling (2000) AEX-804, fungal pathogens and mineral deficiency symptoms appear below VPD value of 0.43 kPa and disease infection can be most damaging below VPD value of 0.2 kPa. It is therefore recommended that the VPD of greenhouse air should be kept above 0.20 kPa. The Ideal range of VPD for most greenhouse crops is between 0.8 to 0.95 kPa (Argus Control Systems Ltd., 2009). Several methods for estimating vapor pressure deficits and RH have been analyzed in the study of Castellvi et al. (1996).

For tropical and subtropical conditions, the strategy in greenhouse climate management and its adaptation to the local environment situations are important in improving resource efficiency (Luo et al., 2005). Evaluating performance of ventilation and pad-and-fan systems based on ideal and acceptable VPD requirements for production of tomato (Shamshiri and Wan Ismail, 2012) showed that proper utilization of natural and mechanical ventilation can be a more effective method of providing acceptable growth conditions in a TL-CEPPS compared with pad-and-fan systems. A comparison between different greenhouse covering materials, including polyethylene film, photo-selective red colored film and insect-proof net, for tomato cultivation during summer was carried out by Arcidiacono et al. (2001). It has been reported that by using insect-proof net covered greenhouse, the inside and outside temperature remain similar, while temperature was observed to be rising with the photo-selective film during summer. In this regard, shelter houses that are covered with net insect screens have

gained more popularity in TLPPS due to the likely potential of air temperature and RH that are naturally close to plants desired levels. These structures are generally used to reduce insect migration on the crop and subsequent crop damage (Teitel, 2001), reduce risk of damaged by high rainfall, extreme solar radiation and high wind speeds.

Microcontrollers and Personal Computers (PC) based data acquisition systems have been widely used in different specific plant production applications due to their lower development cost, operational flexibility and environmental adaptability (Thomas *et al*., 1993; Boaventura *et al*., 1997; Mukaro and Carelse, 1999; Ameur *et al*., 2001; Koutroulis and Kalaitzakis, 2003; Rosiek and Batlles, 2008; Junxianga and Haiqing, 2011). The purpose of this project was to monitor air VPD in a TL shelter-house plant production by means of a custom-designed, low-cost accurate real-time data acquisition system that continuously collects and stores temperature and RH data for VPD calculation. The results of this study will be used in the database of a decision support system for TL-CEPPS of tomato.

METHODOLOGY

Three combined temperature and RH sensor modules, including, two digital SHT11 and SHT15 sensors (Sensirion, AG, Switzerland, 2008) and one analog HSM-20G (2013), (Shenzhen Mingjiada Electronics LTD, Futian Shenzhen, China) were directly connected to three microcontroller units in order to minimize data collection errors and avoid possible hardware interruptions. The DAQ processing parts contained Parallax BS2P24/40 microcontroller on BASIC (2005) Stamp prototype board (Parallax Inc, Rocklin, CA), programmable in Basic language (Fig. 1), Peripheral Interface Controller (PIC) model PIC16F877 (Microchip, 2003) (Microchip Technology Inc, Chandler, AZ) on BizChip (Bizchip Sdn Bhd,

Selangor, Malaysia, 2008) development board programmable in C (C Compiler Brookfield, WI, 2006), (Fig. 2) and ATmega328P (Atmel®, San Jose, CA) on the open source Arduino Uno prototyping platform programmable in Arduino sketch environment software with C language (Barnet *et al*., 2006) (Fig. 3). These microcontrollers were selected based on the prototype board availability, small size and inexpensive development cost that made them suitable for research trials. It should be noted that all vital components (i.e., clock generator, memory and power regulator) for operating microcontroller, as well as direct programming and access to input/output pins were provided by the corresponding prototype board. External Electrically Erasable Programmable Read-Only Memory (EEPROM) was used with BASIC Stamp and PIC and a micro Secure Digital (SD) card board was used with Arduino Uno board for storing larger amount of sensor data.

All prototype boards were equipped with Liquid-Crystal Display (LCD) and serial port RS-232 communication cable (bidirectional with maximum baud speed up to 115200 bites/sec (bps)) for transferring and storing collected data in PC. In addition, the BizChip startup board included 8 Light Emitting Diodes (LED), buzzer, voltage regulator, LM35 temperature sensor (LM35, 2000 National
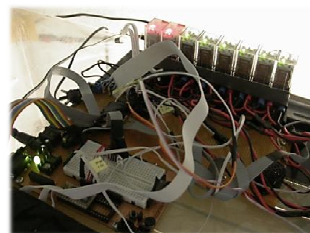
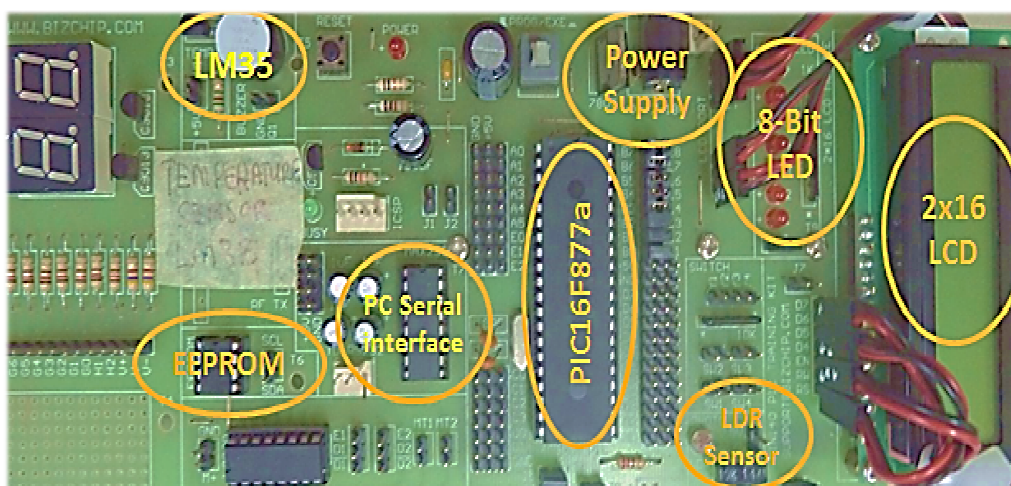Fig. 1: Basic stamp data acquisition platform
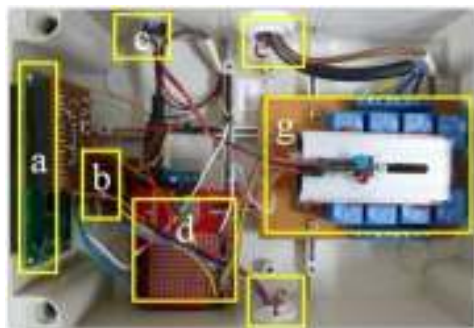
Fig. 2: BizChip PIC development board

Fig. 3: Arduino uno data acquisition platform, (a) LCD, (b) HSM20G sensor circuit connection, (c) power supply, (d) micro SD card board on top of ardunino board, (e) output connection, (f) sensor input, (g) relay circuit board

Semiconductor Corporation, Santa Clara, CA), HIH-4030/31 Series Humidity Sensors (2008) (Honeywell, Minneapolis, MN) with direct input to the microcontroller and Light Dependent sensor (LDR) producing 0 to 5 Voltage Direct Current (VDC) analogue output. Major components on the Arduino Uno microcontroller board included ATmega328 microcontroller operating at 5V with 2 KB of RAM, 32 KB of flash memory for storing programs and 1 KB of EEPROM for storing parameters, a 16 MHz crystal oscillator, digital input/output pins, USB connection, power jack and a reset button. The final DAQ boards with sensors connections and other complementary components have been shown in Fig. 4 and 5. For the purpose of testing DAQ system before installing on the

actual plant, each unit was equipped with a ULN2803A (2005) relay driver Darlington transistor array (Texas Instrumentation, Dallas, TX) for running 8-relays that controlled a lab scale experimental plat form through 8 actuators, including 6 DC fans, one artificial light and one unit of dehumidifier (Fig. 6).

RESULTS AND DISCUSSION

The DAQ system was installed on a 40 m^2 TL shelter-house (Fig. 7) located at the Universiti Putra Malaysia agricultural experimental field (Latitude = 3°0'9.8094" and Longitude = 101°42'11.2926"). The combined temperature and RH sensors were placed inside Okra (Abelmoschus esculentus) plants canopy (Fig. 8) that had been planted in three rows of total 15 polybags in the shelter-house. The VPD sensor was placed in the field, close to the canopy with air around the sensor homogenized by using a plastic shelter. Sample temperature and RH data for VPD calculations were continuously collected every 60 sec, for 6 days, from April, 15 to April 17 and April, 22 to April, 24, 2013. An average of the three readings was then calculated and plotted in Fig. 9 and 10 as the temperature and RH of the air inside plant canopy in the 6 days respectively. The reason for such a long term monitoring was to take into account the effects of solar radiation, climate variations and wind speed. VPD was calculated according to the internationally accepted formulation (Murray, 1967) for saturation vapor pressure that is most widely used by meteorologists and was plotted versus temperature in Fig. 11. The
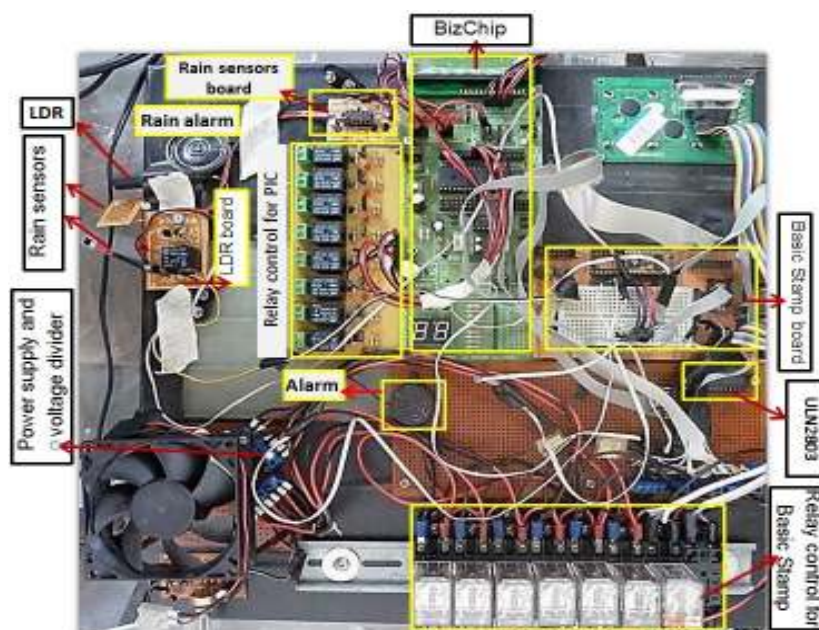

Fig. 4: Final DAQ system with BS2P24/40 basic stamp and PIC16F877 BizChip microcontroller board, SHT11, SHT15, LDR and rain sensors, two independent arrays of 8-relays control, two system alarm, voltage divider and wire connections
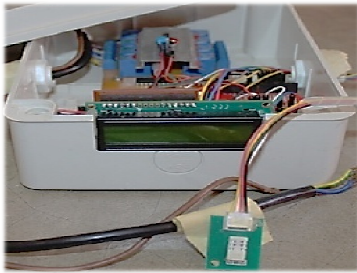
Fig. 5: Final DAQ system with arduino uno microcontroller board and HSM20G combined temperature and RH sensor
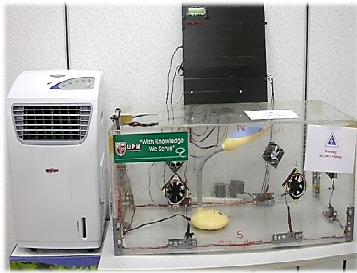

Fig. 6: Testing bench with sensors and actuators for experiment and troubleshooting data acquisition systems

Fig. 7: The shelter-house under study, located at located at the Universiti Putra Malaysia agricultural experimental field (latitude = 3°0' 9.8094" and longitude = 101°42'11.2926")

Fig. 8: Shelter-house with, a) location of DAQ, b) an okra (abelmoschus esculentus) plant

nonlinear correlation that is observed between temperature and VPD data was describe with squared polynomial model given below with a coefficient of determination (R^2) equal to 0.976. This model was successfully used for VPD prediction based on temperature inputs. Plots of actual VPD data versus predicted VPD values have been provided in Fig. 12:
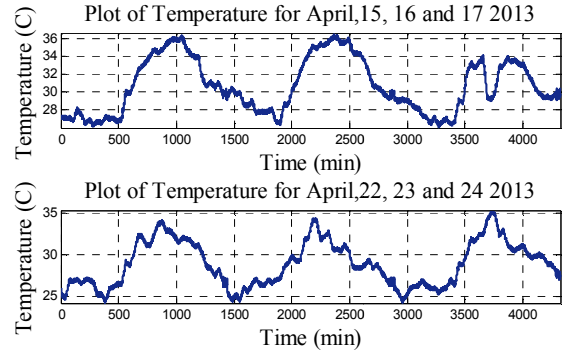

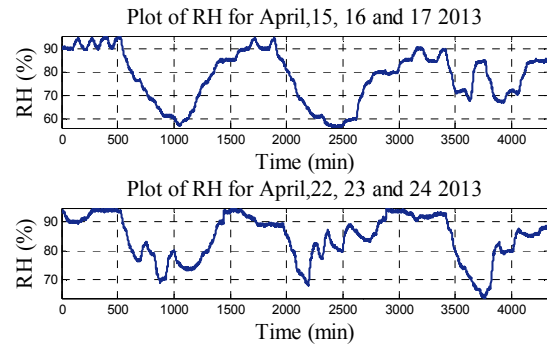Fig. 9: Plots of temperature in the 6 days of experiment

Fig. 10: Plots of RH in the 6 days of experiment
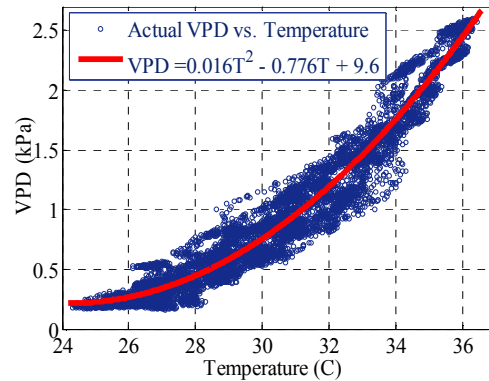
Fig. 11: Plot of VPD vs. temperature with the squared polynomial prediction model

$$VPD = f(T) = 0.01602T^2 - 0.7757T + 9.603$$

According to the descriptive statistics summary of the data (Table 1), the mean value for VPD was 0.87 kPa which is in the comfortable zone for most crop growths. The statistical details for specific data collection day have been provided separately for temperature, RH and VPD in Table 2 to 4, respectively. The results of Analysis of Variances (ANOVA) given in Table 5, rejected the hypothesis that sample data have equal means in different days of experiment. In the other words, there was not enough evidence to

Table 1: Descriptive statistics summary of the collected data in the 6 days of experiment

Parameters	Mean	S.D.	Min.	Q1	Median	Q3	Max.	Range
Temperature (°C)	29.84	3.00	24.32	27.08	29.54	32.17	36.44	12.13
RH (%)	81.32	10.21	56.44	74.32	84.09	90.00	95.41	38.97
VPD (kPa)	0.87	0.62	0.16	0.36	0.65	1.20	2.60	2.44

Max.: Maximum; Min.: Minimum; S.D.: Standard deviation

Table 2: Temperature data statistics in each day of experiment

Days	Date	Mean	S.D.	Min.	Q1	Median	Q3	Max.	Range
1	15/04	30.76	3.39	26.14	27.11	30.72	34.16	36.36	10.22
2	16/04	31.51	3.04	26.33	28.80	30.56	34.72	36.44	10.11
3	17/04	30.00	2.36	26.11	28.27	29.51	32.64	34.11	8.01
4	22/04	29.02	2.74	24.32	26.66	28.51	31.70	34.13	9.81
5	23/04	28.71	2.42	24.44	26.79	28.57	30.55	34.35	9.91
6	24/04	29.06	2.82	24.32	26.27	29.11	31.07	35.21	10.89

Max.: Maximum; Min.: Minimum; S.D.: Standard deviation

Table 3: Relative humidity data statistics in each day of experiment

Days	Date	Mean	S.D.	Min.	Q1	Median	Q3	Max.	Range
1	15/04	78.82	12.60	56.91	67.17	79.79	90.69	95.41	38.50
2	16/04	75.45	12.75	56.44	61.29	77.81	87.36	94.68	38.24
3	17/04	80.05	6.90	67.08	72.29	82.84	85.01	90.63	23.56
4	22/04	83.93	7.89	69.27	77.07	82.57	91.28	94.54	25.27
5	23/04	85.59	6.22	68.19	81.89	86.75	89.64	94.51	26.32
6	24/04	84.10	8.97	63.78	79.44	86.20	92.11	94.69	30.90

Max.: Maximum; Min.: Minimum; S.D.: Standard deviation

Table 4: Vapor pressure deficit data statistics in each day of experiment

Days	Date	Mean	S.D.	Min.	Q1	Median	Q3	Max.	Range
1	15/04	1.06	0.78	0.16	0.33	0.90	1.79	2.59	2.43
2	16/04	1.25	0.81	0.19	0.50	0.98	2.15	2.60	2.42
3	17/04	0.89	0.42	0.32	0.57	0.72	1.35	1.72	1.40
4	22/04	0.70	0.42	0.18	0.30	0.69	1.08	1.65	1.47
5	23/04	0.60	0.35	0.17	0.36	0.52	0.81	1.72	1.55
6	24/04	0.70	0.51	0.18	0.27	0.56	0.91	2.03	1.85

Max.: Maximum; Min.: Minimum; S.D.: Standard deviation

Table 5: ANOVA results of hypothesis testing of equal means

Source of variation	S.S.	df	M.S.	F	p-value	F-critical
	Temperature					
Between groups	8866.3030	5	1773.261	225.2630	1e-226	2.215
Within groups	68060.9400	8646	7.871957			
Total	76927.2400	8651				
	Relative humidity					
Between groups	111104.9000	5	22220.98	238.3061	3.6e-239	2.215
Within groups	806201	8646	93.24554			
Total	917305.9000	8651				
	Vapor pressure deficit					
Between groups	427.1597	5	85.43193	266.7666	4.6e-266	2.215
Within groups	2768.8790	8646	0.32025			
Total	3196.0390	8651				

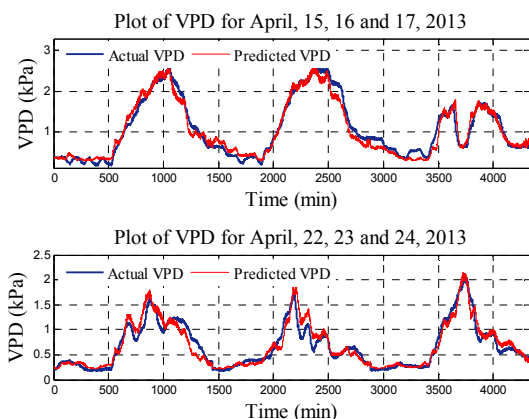S.S.: Sum of square; M.S: Mean square

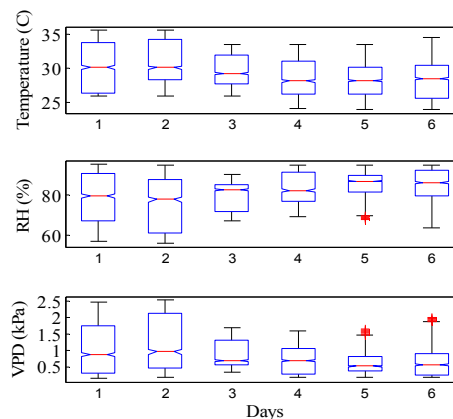Fig. 12: Plots of actual and predicted VPD in the 6 days of experiment

Fig. 13: Box plots of temperature, RH and VPD in each day of experiment
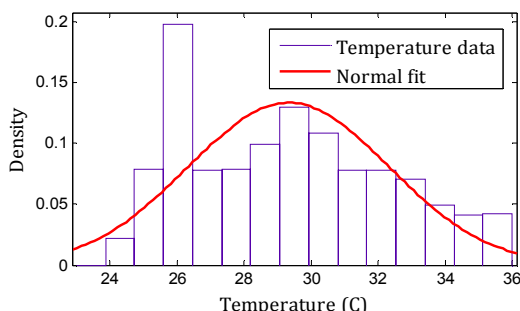
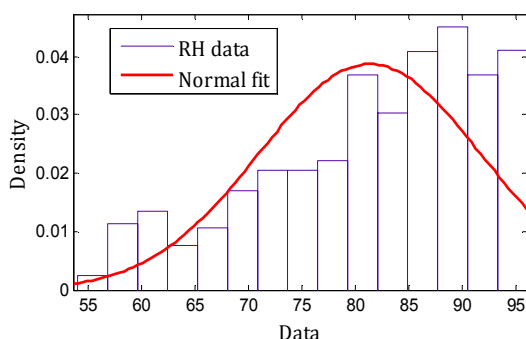Fig. 14: Density distribution of temperature

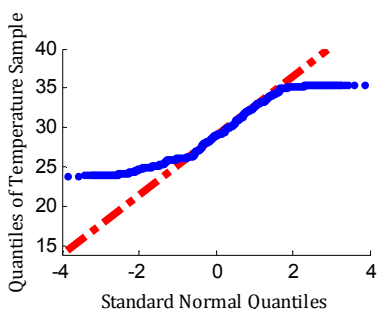Fig. 15: Density distribution of RH

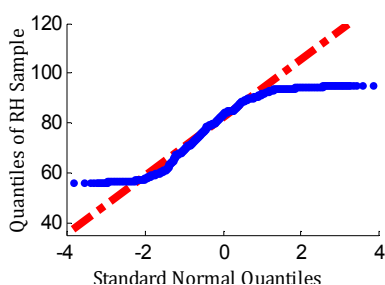Fig. 16: QQ plot of temperature data versus standard normal

Fig. 17: QQ plot of RH data versus standard normal

support that the average daily temperature, RH and VPD values did not vary in these 6 days. In order to study the distribution of data, each sample has been shownby means of box plots (Velleman and Hoaglin, 1981) in Fig. 13. The hypothesis to be tested was that the collected temperature and RH samples follow normal distribution. To test this claim, density distribution and QQ plot was provided as shown in Fig. 14 to 17. It can be seen from plots of normal distribution fit in Fig. 14 and 15 and Q-Q plots in Fig. 16 and 17, that both temperature and relative humidity data have significant deviation from normality on the tails sides. The one-sample Kolmogorov-Smirnov test (Corder and Foreman, 2009) at the 5% significance level was also used to test the hypothesis that the collected temperature and RH data follow a normal distribution. Based on the results, it was concluded with 99% confidence that that neither collected temperature nor RH data follow normal distribution.

CONCLUSION

The high demands for quality agricultural product necessitates practicing various methods of modern technologies including automation and mechanization in different scopes of plant production system. The crop cultivation in TL environments by using the enhanced agricultural machine has not reached the optimal crop production as crop is still subjected to various stresses such as heavy rainfall, insects and extreme solar radiation. The high temperature and ambient RH are major issues in providing ideal environmental condition. This research study provided a better understanding of TL environments by addressing relatively long-term trends in temperature, RH and VPD. Major steps involved in this project included DAQ hardware/software interfacing, laboratory tests and calibrations, real-time monitoring of temperature and RH from the actual shelter-house, VPD calculations and data analyzing. The designed DAQ system was successfully used for data collection and results showed that the average VPD is in the ideal range for plant growth. It can be concluded that perhaps the best way to improve performances of plant production systems in TL environments is to use the local information and the knowledge about crop itself. This is however a hypothesis to be tested, that by only applying appropriate natural and mechanical ventilation techniques, as in shelter houses, the probability of achieving successful production of a particular plant at its different growth stages would be higher that closed environment with evaporative cooling.

REFERENCES

Ajwang, P.O. and H.J. Tantau, 2005. Prediction of the effect of insect proof screens climate in naturally ventilated greenhouse in humid tropical climates. Acta Hortic., 691: 449-456.

Ameur, S., M. Laghrouche and A. Adane, 2001. Monitoring a greenhouse using a microcontroller-based meteorological data acquisition system. Renew. Energ., 24:19-30.

Arcidiacono, C., A.D. Emilio, R. Mazzarella and C. Leonardi, 2001. Covering materials to improve the microclimate during summer in hot climates. Acta Hortic., 719: 214.

Argus Control Systems Ltd., 2009. Understanding and Using VPD, Argus Application Note. Argus Control Systems Ltd., Canada. Retrieved form: http://www.arguscontrols.com/resources/VPD_Application_Note.pdf, (Accessed on: Sep. 10, 2013).

ATmega328P data sheet, 8161D-AVR-10/09. Atmel®, San Jose, CA. Retrieved form: http://www.atmel.com/Images/doc8161.pdf.

Barnet, R.H., S. Cox and L. O'Cull, 2006. Embedded C programming and the Atmel AVR. 2nd Edn., Delmar Learning, New York.

BASIC, Stamp Syntax and Reference Manual, Version 2.2. 2005. Parallax Inc. 599 Menlo Drive, Suite 100. Rocklin, California 95765, USA. Retrieved form: http://www.parallax.com, (Accessed on: August 01, 2013).

Bizchip Sdn Bhd, Selangor, Malaysia, 2008. MINI40 PIC Training Kit and BIZ025/40PIN PIC Startup Kit User Manual, Sdn Bhd. Retrieved form: http://www.bizchip.com/, (Accessed on: September 10, 2013).

Boaventura, J.C., C. Couto and A.E. Ruano, 1997. Real-time parameter estimation of dynamic temperature models for greenhouse environmental control. Control Eng. Pract., 5(10): 1473-1481.

Castellvi, F., P.J. Perez, J.M. Villar and J.I. Rosell. 1996. Analysis of methods for estimating vapor pressure deficit and relative humidity. Agr. Forest Meteorol., 82: 29-45.

C Compiler Brookfield, WI, 2006. Reference Manual Version 4, Brookfield, WI 53008.

Corder, G.W. and D.I. Foreman, 2009. Nonparametric Statistics for Non-statisticians: A Step-by-step Approach. John Wiley, Hoboken, pp: 264.

El-Sharkawy, M.A., J.H. Cock and A.D.P. Hernandez, 1986. Stomatal response to air humidity and its relation to stomatal density in a wide range of warm climate species. Photosynth. Res., 7(2): 137-149.

HIH-4030/31 Series Humidity Sensors, 2008. Minneapolis: Honeywell International. Retrieved from the World Wide Web: http://sensing.honeywell.com/index.php?ci_id=51625&la_id=1.

HSM-20G, 2013. Shenzhen Mingjiada Electronics LTD, Futian Shenzhen, China. Retrieved form: http://www.seeedstudio.com/depot/datasheet/HSM-20G.pdf, (Accessed on: September 10, 2013).

Junxianga, G. and D. Haiqing, 2011. Design of greenhouse surveillance system based on embedded web server technology. Procedia Eng., 23: 374-379.

Koutroulis, E. and K. Kalaitzakis, 2003. Development of an integrated data-acquisition system for renewable energy sources systems monitoring. Renew. Energ., 28: 139-152.

LM35, 2000. Precision centigrade temperature sensors data sheet. National Semiconductor.

Luo, W., H.F. DeZwart, J. Dai, S. Wang, C. Stanghellini and C. Bu, 2005. Simulation of greenhouse management in the subtropics, Part I: Model validation and scenario study for the winter season. Biosyst. Eng., 90(3): 307-318.

Microchip, 2003. PIC16F87X Data Sheet 28/40/44- Pin Enhanced Flash Microcontrollers. DS39582B. Technology Inc. Retrieved form: http://ww1.microchip.com/downloads/en/devicedoc/39582b.pdf, (Accessed on: September 10, 2013).

Mukaro, R. and X.F. Carelse, 1999. A microcontroller-based data acquisition system for solar radiation and environmental monitoring. IEEE T. Instrum. Meas., 48(6): 1232-1238.

Murray, F.W., 1967. On the computation of saturation vapor pressure. J. Appl. Meteorol., 6: 203-204.

Pettigrew, W.T., J.D. Hesketh, D.B. Peters and J.T. Wooley, 1990. A vapor pressure deficit effect on crop canopy photosynthesis. Photosynth. Res., 24: 27-34.

Pregner, J.J. and P.P Ling, 2000. Greenhouse Condensation Control. Fact Sheet (Series) AEX-800. Ohio State University Extension, Columbus, OH.

Rosiek, S. and F.J. Batlles, 2008. A microcontroller-based data-acquisition system for meteorological station monitoring. Energ. Convers. Manage., 49: 3746-3754.

Sensirion, AG, Switzerland, 2008. SHT1x Humidity and Temperature Sensor Datasheet. Sensirion, the Sensor Company, Version 4.0.

Shamshiri, R. and W.I. Wan Ismail, 2012. Performance evaluation of ventilation and pad-and-fan systems for greenhouse production of tomato in lowland Malaysia. World Res. J. Agri. Biosyst. Eng., 1(1): 1-5.

Teitel, M., 2001. The effect of insect proof screens in roof openings on greenhouse microclimate. Agr. Forest Meteorol., 110(1): 13-25.

Thomas, A., A. Ganesan and S.A. Mujeeb, 1993. Solar irradiance monitor. Renew. Energ., 3(6-7): 599-606.

ULN2803A, 2005. Texas Instruments Incorporated Darlington transistor array data sheet. Revised NOV.

Velleman, P.F. and D.C. Hoaglin, 1981. Applications, Basics and Computing of Exploratory Data Analysis. Duxbury Press, Pacific Grove, CA.