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**Master's Thesis of Engineering**

**Development of Fuzzy Logic  
Controlled Hydroponic System  
for Home Cultivating Sweet Basil**

스위트 바질 재배를 위한  
가정용 퍼지 제어 수경재배 시스템 개발

**February 2021**

**Graduate School of Agriculture and Life Sciences  
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Major of Biosystems Engineering**

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# **Development of Fuzzy Logic Controlled Hydroponic System for Home Cultivating Sweet Basil**

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# Abstract

As environmental pollution gets more severe demands for indoor farming have been rising with a subsequent increase in studies related to it. Research on stable indoor cultivation systems that cannot be affected by outdoor climate conditions and efficient systems that can maximize production under space constraints is advancing rapidly. However, most studies focus on industrial farming or large-scale production. Small-scale cultivation for households requires equal attention. This study aimed to design household hydroponic systems automatically controlled by fuzzy logic with Raspberry Pi 4 and using the Python programming language. Fuzzy logic control (FLC) was adopted to resolve ambiguity and improve the environmental control of the inside chamber. For the FLC, three input and seven output variables were used. The input variables were temperature, humidity, and growth stage (duration) and the output variables were fan, mist, two heaters (heater1 and heater2), and three RGB LEDs. Six FLC rules were with these variables. The FLC ensured that the three lights operate for three different cultivating periods. Each growth stage required different light quality and density inducing different volatile compounds and flavors of plants. The results showed that inner temperature of the control uses airflow to maintain the temperature at approximately 21 – 26 °C (average of 21.24 °C) compared to the outer temperature of 19.8 °C. Furthermore, the mean value of inner humidity is 75.58 %, the outer humidity was 16.57 %. However, the controlled humidity should have been maintained at an approximately lower temperature of the level of 60 - 65 %. To address this problem, the rules and membership functions were analyzed by Pearson's correlation coefficients. Because fan's correlations with heaters, humidity and mist were lower than expected, it was assumed that the fan made a significant contribution to the problem. Besides, comparison between simulation and actual operation were carried out and it was noticed

that heaters' actual work was done inappropriately breaking the boundary of simulation. Finally, light quality was controlled by the FLC based on three light regimes upon days of duration; blue light for germination, red light for vegetative growth and green light for flowering stage. The light control will be more accurate if the growth stage is estimated by machine vision with an RGB camera.

**Keyword:** Household, Hydroponic system, Sweet Basil, Fuzzy Logic Control, Growth Stage, LED Lights

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# Table of Contents

Abstract .....	iii
Table of Contents .....	v
List of Tables .....	viii
List of Figures .....	ix
Chapter 1. Introduction .....	1
1.1. Study Background.....	1
1.2. Review of Literature .....	4
1.2.1. Urban farming and Urban agriculture .....	4
1.2.2. Household appliances in agriculture.....	7
1.2.3. Lighting for cultivation.....	9
1.2.4. Basil ( <i>Ocimum Basilicum L.</i> ) .....	13
1.2.5. Growth stages of Plants .....	15
1.2.6. Fuzzy Logic Control Systems in Agriculture.....	18
1.3. Research Purpose and Significance.....	20
1.3.1. Research Objectives.....	20
1.3.2. Significance .....	21
Chapter 2. Materials and Methods .....	22
2.1. Preliminary Performance Test of Conventional Control System .....	22
2.1.1. Purpose of Preliminary Test.....	22
2.1.2. Hardware Design .....	23
2.1.2.1. Wall-mount and standing type (two ways) .....	23
2.1.2.2. Modular type .....	25
2.1.3. Hardware Operating Test With Arduino.....	26
2.1.3.1. Materials .....	26
2.1.3.2. Overall system .....	28

2.1.4. Fuzzy Logic Simulation With MATLAB and Arduino	29
2.2. Experimental Hardware Setup and Configuration	32
2.2.1. Materials	32
2.2.2. Overall Circuit and System Setup	36
2.2.3. Fuzzy Logic Control System	39
Chapter 3. Results and Discussion	48
3.1. Preliminary Test Results	48
3.1.1. Hardware Work	48
3.1.2. Software Work	49
3.1.3. Limitations	50
3.2. Experiment Results	51
3.2.1. Simulation	51
3.2.1.1. Rule View	51
3.2.1.2. Surface View	54
3.2.2. Hardware operations	55
3.2.2.1. Fan	55
3.2.2.2. Mist	55
3.2.2.3. Heaters	56
3.2.2.4. LED	57
3.2.3. Results of Integrated system	58
3.2.3.1. Unprocessed data of temperature and humidity	58
3.2.3.2. Outliers removal	61
3.2.3.2.1. Statistics	61
3.2.3.2.2. Data Visualization	63
3.2.3.3. LED Changes	66
3.2.4. Correlation between Input and Output variables	70
3.2.4.1. Group1 (Temperature, Humidity)	69
3.2.4.2. Comparison between results of simulation and actual operation	75

<b>Chapter 4. Conclusions .....</b>	<b>80</b>
<b>Bibliography.....</b>	<b>84</b>
<b>Abstract in Korean .....</b>	<b>88</b>

## **List of Tables**

<b>Table 1 Fuzzy associative matrix (Group 1).....</b>	<b>47</b>
<b>Table 2 Fuzzy associative matrix (Group 2).....</b>	<b>47</b>
<b>Table 3 Statistical results of temperature and humidity .....</b>	<b>61</b>
<b>Table 4 LED Changes.....</b>	<b>68</b>

## List of Figures

<b>Fig. 1 Household vegetable cultivator from LG Electronics (Left) and Samsung Electronics (Right) at CES 2020. ....</b>	<b>7</b>
<b>Fig. 2 Phytochemical enrichment under blue light.....</b>	<b>10</b>
<b>Fig. 3 Efficiency, life span, emissions, and electricity usage comparison of HPS, CFL and LEDs .....</b>	<b>12</b>
<b>Fig. 4 Principal growth stages of plants.....</b>	<b>15</b>
<b>Fig. 5 Phenotypic characteristics of each stage of plant growth according to BBCH Growth Scale (1) .....</b>	<b>16</b>
<b>Fig. 6 Phenotypic characteristics of each stage of plant growth according to BBCH Growth Scale (2) .....</b>	<b>17</b>
<b>Fig. 7 Configuration of FLC .....</b>	<b>19</b>
<b>Fig. 8 Each separated parts of a prototype for the wall-mount type. .</b>	<b>23</b>
<b>Fig. 9 Two types (Standing and Wall-mount) in one design.....</b>	<b>24</b>
<b>Fig. 10 Modular type with adjustable height and width to fit the available space.....</b>	<b>25</b>
<b>Fig. 11 Images of positions of the prototype at home .....</b>	<b>25</b>
<b>Fig. 12 Final control parts.....</b>	<b>27</b>
<b>Fig. 13 The modular type working by mobile application manually selecting plant growth stages .....</b>	<b>28</b>
<b>Fig. 14 Fuzzy logic (Mamdani) .....</b>	<b>29</b>
<b>Fig. 15 Variables and Membership functions.....</b>	<b>30</b>
<b>Fig. 16 Sensors, actuators and other components used in the experiment .....</b>	<b>34</b>
<b>Fig. 17 Setup with sensors and actuators in a cultivator .....</b>	<b>35</b>
<b>Fig. 18 Circuit Schematic .....</b>	<b>35</b>
<b>Fig. 19 Overall system; Raspberry Pi 4, circuit and a controlled cultivator.....</b>	<b>37</b>
<b>Fig. 20 Circuit .....</b>	<b>38</b>

<b>Fig. 21 Cultivator’s structural form .....</b>	<b>38</b>
<b>Fig. 22 The fuzzy control system including input and output variables.....</b>	<b>40</b>
<b>Fig. 23 Membership functions of input parameters .....</b>	<b>41</b>
<b>Fig. 24 The duty cycle.....</b>	<b>43</b>
<b>Fig. 25 Membership functions of output variables (1) .....</b>	<b>44</b>
<b>Fig. 26 Membership functions of output variables (2) .....</b>	<b>45</b>
<b>Fig. 27 Operations of components.....</b>	<b>48</b>
<b>Fig. 28 Setting values and its result.....</b>	<b>49</b>
<b>Fig. 29 Rule View of Fuzzy Logic Simulation .....</b>	<b>53</b>
<b>Fig. 30 Surface View of Fuzzy Logic Simulation .....</b>	<b>54</b>
<b>Fig. 31 Fan in operation together with the numbers of duty cycle .....</b>	<b>55</b>
<b>Fig. 32 Mist generator in operation together with the numbers of duty cycle.....</b>	<b>55</b>
<b>Fig. 33 Heater1 and Heater2 in operation together with the numbers of duty cycle.....</b>	<b>56</b>
<b>Fig. 34 LED in operation changing light quality together with the numbers of duty cycle and signals.....</b>	<b>57</b>
<b>Fig. 35 Concept of Boxplots. ....</b>	<b>58</b>
<b>Fig. 36 Trends in inner and outer temperature based on unprocessed data including outliers.....</b>	<b>59</b>
<b>Fig. 37 Box plots for comparison between inner and outer temperature based on unprocessed data including outliers.....</b>	<b>59</b>
<b>Fig. 38 Trends in inner and outer humidity based on unprocessed data including outliers .....</b>	<b>60</b>
<b>Fig. 39 Box plots for comparison between inner and outer humidity based on unprocessed data including outliers.....</b>	<b>60</b>
<b>Fig. 40 Trends in inner and outer temperature based on processed data excluding outliers .....</b>	<b>63</b>
<b>Fig. 41 Box plots for comparison between inner and outer temperature based on processed data excluding outliers.....</b>	<b>64</b>

<b>Fig. 42 Trends in inner and outer humidity based on processed data excluding outliers.....</b>	<b>65</b>
<b>Fig. 43 Box plots for comparison between inner and outer humidity based on processed data excluding outliers.....</b>	<b>65</b>
<b>Fig. 44 Red, Green, and Blue of LEDs changes upon days of duration</b>	<b>68</b>
<b>Fig. 45 Relations between temperature and three output variables; fan, mist, and heaters (heater1 and heater2).....</b>	<b>70</b>
<b>Fig. 46 Relations between humidity and three output variables; fan, mist, and heaters (heater1 and heater2) .....</b>	<b>71</b>
<b>Fig. 47 Heatmap describing correlations between two input variables (temperature, humidity) and four output variables (fan, mist, heater1, heater2) based on Pearson's correlation coefficients.....</b>	<b>74</b>
<b>Fig. 48 Correlations in Simulation .....</b>	<b>77</b>
<b>Fig. 49 Correlations in Actual Operation .....</b>	<b>78</b>
<b>Fig. 50 Overlap Area in Simulation and Actual Operation .....</b>	<b>79</b>

# Chapter 1. Introduction

## 1.1. Study Background

The continuously increasing overpopulation and pollution, and decreasing number of farmers are major causes of food shortage. Consequently, indoor farming, using less land and resistant to adverse climate conditions, is being considered as paramount solutions.

A disadvantage is the high costs of the initial set up of the system, whereas the continuously increasing cultivating crops, such as lettuce, are inexpensive.

To address these problems, some farmers are attempting to use special crops such as sprout garlic and sprout ginseng to sell exclusively and expensively. However, these crops lack popular appeal and, therefore, market potential.

Sweet basil is a typical example. Its value has been assessed in the study of Liaros *et al.* (Liaros, Botsis, and Xydis 2016) as a competitive crop. The demand for this herb increases with increasing consumers' awareness of the unique aroma and taste of this herb. The demand is not at its peak so the selling price is in the upper section.

To reduce the disadvantages, researchers have attempted to develop efficient systems for indoor farming with several methods aiming at low cost and high productivity. Among them, fuzzy logic control (FLC) is propose to achieve this goal.

FLC is considered as a optimal methodology because it records the approximate and inexact nature with a set of linguistic control strategy. It differs from classical logic systems; the boolean. It can automatically manage complex and nonlinear systems based on multiple rules and membership functions representing the degree of truth.

Therefore, FLC is often used in household appliances management. FLC has been applied to green houses, and scarcely in home farming appliances.

However, household farming appliances is receiving significant attention recently. Particularly, LG electronics and Samsung electronics developed household harvesting appliances shaped in refrigerators in CES 2020. This indicates increasing demand for household growing appliances in market.

For LG electronics', several functions are explained; maintaining temperature and wick-based water management, forced air circulation, and built-in LED lights. In addition, several cultivators have been developed by startups.

Nonetheless, there are several limitations of these cultivating systems.

First, in lighting difference upon plant growth stage.

Lighting requires adjustment in wavelength and intensity because plants require different light regimes based on species and growth stages. Two important points are considered. Systems should observe and consider growing plant's growth stages and species. Furthermore, systems ought to be able to operate red, green and blue lights independently.

However, existing products or systems have used some fixed ratios of three

lights in the growth stages and species. Because lighting has a significant impact on the components of plants causing a change in taste, and a reduction in the quality of harvest. Therefore, it is imperative to develop a grade in cultivating field.

Second, in fuzzy logic.

Two things are observed. There is no study that considers the three lights separately as output variables and there is no proposed method to supplement and improve designed fuzzy logic control.

Third, no study describes standards or elements to consider in building household harvesting appliances.

After arranging and considering of these factors, this study is organized and performed to address the shortcomings and conjugate merits.

## **1.2. Review of Literature**

### **1.2.1. Urban farming and Urban agriculture**

Food security is considered as a global problem because environmental pollution is increasing. Particularly, air pollution, soil contamination and climate changes have significantly reduced the available land for cultivation.

Furthermore, increasing population increases the demand for food production. According to a UN report, the world population is proposed to reach 9.7 billion in 2050, increasing by 35 %, and can peak to nearly 11 billion around 2100.

To satisfy this exponentially increasing future demand in 2050, the United Nation's Food and Agriculture Organization estimates that agricultural production will have to increase by sixty percent.

Additionally, in 1950, the average farmer fed 27 people. Now, it has risen to more than 150 (*How will farmers feed the world's population 30 years from now? / TheHill*, 03/09/17). The total population fed per farmer will increase. Furthermore, the proportion of working-age population is reducing (*World population projected this to reach 9.8 billion in 2050, and 11.2 billion in 2100 / UN DESA / United Nations Department of Economic and Social Affairs*, 21/06/17).

Herein, urban farming proposed and considered by several researchers and governments. From studies and markets, the global urban farming market accounted for \$210 billion in 2017 and can reach \$288.71 billion by 2026 (*Global Urban Farming Market Nears \$289 Billion by 2026 - Market*

*Share Analysis of the Top Industry Players*, 30/08/19). There are several directions and method; soilless or soil-based farms, outdoor or indoor farming, and types of farming such as vertical farming (Tagle et al. 2018), hydroponic system (Daud, Handika, and Bintoro 2018), building integrated farming (Khan, Aziz, and Ahmed 2018), rooftop farming and community farms (Goodman and Minner 2019).

These methods aim to improve the efficiency of land use, maximizing yields in narrow spaces and developing abandoned lands. By urban agriculture, people can reduce food miles; the miles that a food item is transported from the producer to the consumer, in unit of measurement of fuel used for the transportation.

That is, people can significantly reduce carbon dioxide that triggers climate change. Furthermore, urban inhabitants can produce their food yielding sustainability in the cities. Farming no longer belongs only to farmers.

For indoor gardening, there is a significant advantage of the ability to optimally manage the environment. Controlled environment agriculture (CEA) is beneficial to farmers because CEA addresses protecting crops from pests and diseases. Also, it enables workers to produce crops all year round by managing the environment appropriately. Vertical farming and hydroponics are the principal systems applied in CEA.

New York is the leading city in CEA. However, Goodman and Minner showed that commercial CEA farms are unlikely to replace a significant

portion of city's production because of the high startup costs and the high knowledge requirement from farmers to produce high-value crops. Without government's financial support, it is difficult to initiate.

### 1.2.2. Household appliances in agriculture

Recently, the global household electronics companies LG Electronics and Samsung Electronics introduced indoor vegetable cultivators for home use in CES 2020. This indicates that the demand for home gardening is increasing.



**Fig. 1 Household vegetable cultivator from LG Electronics (Left) and Samsung Electronics (Right) at CES 2020.**

In developed countries, home gardening is getting common and is a developing culture. According to National Gardening Survey in America, 77 % of American households are performing food gardening and baby boomer generation born between 1946 and 1964 steadily occupies 35 % and millennials born between 1981 and 1996 occupy 29 % although it is steadily increasing. Therefore, food gardening market is considered to be promising. Furthermore, the expense of households on home gardening was \$47.8 billion and the average expense per home was \$503 in 2018. This increased by \$100 compared to that of the previous year. (Gardening reaches an All Time High n.d.) In the United Kingdom €7.5 billion was spent on household

horticulture products in 2017 according to the report by HTA.

Euromonitor International has reported that gardening is becoming a popular trend in South Korea, owing to high interest in the quality of the air indoors and in private living spaces. Every spring, yellow dust from outside the country covers South Korea, and micro dust is a significant threat to the respiratory system. (Gardening in South Korea | Market Research Report | Euromonitor n.d.)

In addition to these increasing demands and market values, developing household appliances is not simple. Household appliances are severely cost-constrained systems. The ramifications of the severe cost-constraints on appliances are sparse and noisy sensors; slow actuators and bounded controls, low-cost embedded processors that limit the complexity of the control logic, and no models suitable for the management. (Badami and Stephanou 1997)

### 1.2.3. Lighting for cultivation

Plants adapt their growth and physiology according to the ambient conditions. Light modulates plant growth in their development. It affects seed germination, seedling development, transition to flowering, and adaptation to stress responses.

Plants can sense and respond to a range of spectrum, spanning from UV-C (260 nm) to the far-red (720 – 780 nm) regions. Combinations of wavebands in an incident light affect plant growth, metabolism and morphology.

Some light treatments increase volatile content, mass, and antioxidant capacity in Basil. This shows that narrow-bandwidth illumination can induce discrete suites of volatile classes that affect sensory quality in commercial herbs (S. D. Carvalho et al. 2016).

In addition, some studies have shown that appropriate use of LEDs improves production efficiency by phytochemical enrichment as shown on Fig. 2. (Taulavuori et al. 2017)

A novel new light recipe was proposed by Rihan *et al.* (Rihan et al. 2020) Blue light in 450 nm has been used commercially. Two absorbance peaks were observed in the photosynthetically active radiation region at 435 nm and 665 nm, and not 450 nm. It shows that a ratio of 1.4 blue to 1.0 red increased growth and yield compared to a 1:1 ration B/R.

Plant species	Phytochemical	WL (nm)	Reference
Lettuce ( <i>Lactuca</i> sp.)	Vitamin C	460–475	33
Orange ( <i>Citrus</i> sp.)	Phenols	450	34
Monkey-pepper ( <i>Piper</i> sp.)	Sesquiterpenes	450–550	35
Chinese kale ( <i>Brassica</i> sp.)	Total phenols, anthocyanins, antioxidants	470	36
Yarrow ( <i>Achillea</i> sp.)	Monoterpene	430–440 <sup>a</sup>	37
Grape ( <i>Vitis</i> sp.)	Stilbene	440	38
Grape ( <i>Vitis</i> sp.)	Phenols	460	39
Chinese foxglove ( <i>Rehmannia</i> sp.)	Total phenols and flavonoids	450	40
Tartary buckwheat ( <i>Fagopyrum</i> sp.)	Anthocyanins	430	41
Cherry tomato ( <i>Solanum</i> sp.)	Antioxidants	456	42
Grape ( <i>Vitis</i> sp.)	Anthocyanins (sugars)	450	43
<i>Gynura bicolor</i>	Anthocyanins, total phenols and antioxidants	460–463	44
Spearmint ( <i>Mentha</i> sp.)	Terpenoid rich oil	460–475	45
Tartary buckwheat ( <i>Fagopyrum</i> sp.)	Phenols	470	46
Strawberry ( <i>Fragaria</i> sp.)	Anthocyanins	470	47
Bilberry ( <i>Vaccinium</i> sp.)	Anthocyanins	400–500	48
<i>Petunia</i> x hybrid	Methyl benzoate, methyl salicylate	400–500 <sup>a</sup>	49
Rice ( <i>Oryza</i> sp.)	Flavonoid glycosides	450	50
Strawberry	Anthocyanins	405, 465	51
<i>Kalanchoe pinnata</i>	Total phenols and antioxidants	400–500 <sup>a</sup>	52
Red and green lettuce ( <i>Lactuca</i> sp.)	Phenols, antioxidants	456	53

The articles are found in Scopus database on publication years 2013–2017. The keywords used were: 'phytochemical blue light'.  
WL refers to wavelength used in the given study.  
<sup>a</sup> Indirect information.

**Fig. 2** Phytochemical enrichment under blue light.

However, there are inconsistent results reported by studies on light management.

For instance, a study proposed that using only blue and red light is optimal compared to using the three light regimes including green light. Another study proposed that using the three lights including green or yellow light significantly influences plants than using only two lights. (Aldarkazali et al. 2019b; S. M. P. Carvalho et al. 2016)

For decades, researchers have attempted to determine the effect of light management. However, most studies were conducted, irradiating different light wavelengths on each crop and did not adjust from seedling to harvesting.

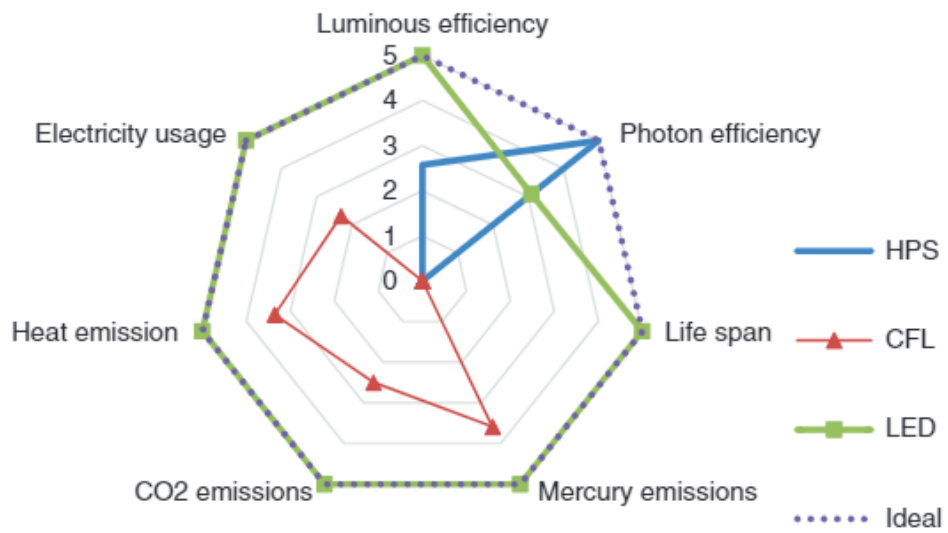
That is, a limited number of experiments shed different wavelengths on

crops in their growth stages. It can be because there are several variables in cultivation to investigate their effect.

Managing light quality in growth level should be appropriately performed because it can significantly improve crop quality. For example, Johkan *et al.* proposed that raising seedlings treated with blue light promoted the growth of lettuce plants after transplanting.

A new attempt in lighting system was implemented recently. Joshi *et al.* observed that a combination of downward lighting and supplemental upward lighting improves plant growth in a closed plant factory with artificial lighting.

Light emitting diode (LED), compact fluorescent light (CFL) lamps, and high pressure sodium (HPS) can be used for lighting. However, owing to their superior properties as shown in Fig. 3, LEDs are replacing traditional lighting systems and used for lighting in plant production in greenhouses and indoor growing systems.



**Fig. 3 Efficiency, life span, emissions, and electricity usage comparison of HPS, CFL and LEDs.**

#### **1.2.4. Basil (*Ocimum Basilicum* L.)**

Basils (*Ocimum Basilicum* L.) grow in several regions in the world. It is herbaceous, 20 – 60 cm long and a white-purple flowering plant from India and Iran. Basil is a species used for commercial seasoning. Fresh and dried basils are widely used in the Mediterranean kitchen in pasta and marine foods. The leaves of basil are used in pharmacy for diuretic and stimulating properties, in perfumes compositions. (Pahlavan, Omid, and Akram 2012)

Basil requires persistent indoor temperatures 70 – 80 °F (21 – 26 °C), particularly a tad cooler in the night cycle although not below 65 °F (18 °C). Basils perish below 50 °F (10 °C). Maintaining the temperatures is the initial step in maintaining suitable humidity levels. The potential water holding capacity of warm air is significantly higher than that of cool air. Air at 65 °F can hold 4 to 5 times moisture compared to that at 25 °F. In aspect of humidity, normal levels of 45 – 75 % required by most plants, basil, however, requires 60 – 65 %. Basil plants will rapidly perish in dry airflow. (Optimizing Hydroponic Basil n.d.)

Because limited available land and deficient agricultural workforce are problems in urban agriculture, multiple-layers-applied-agriculture such as hydroponic system is recommended to maximize efficiency. Exorbitant initial setup cost for this facility is a considerable problem. To address this problem, cultivating high-valued crops in the facility is a countermeasure.

Herein, basil is a preferred crop. There are several reports on basil. Increasing consumer awareness along the promotion of healthy lifestyles

promotes the demand for organic products such as fresh vegetables, spices and herbs. To assess the economic value of crops, we select the following factors, the sell value of the product, cultivable area ratio, specific fresh mass production per plant, PPFD, beta function, taxation, debt ratio, and fixture efficacy as sunlight contribution. From the results, sweet basil was a viable cultivation option. (Liaros, Botsis, and Xydis 2016)

Repeatedly, basil is a significant horticultural crop presenting a complex aroma profile. In addition, it is considered as economical. The culinary herb produces an aroma, primarily composed of terpenes/terpenoids, phenylpropanoids, and fatty-acid-derived volatile molecules significantly appreciated by consumers. (S. D. Carvalho et al. 2016)

### 1.2.5. Growth Stages of Plants

Growth stage significantly affects the quality of plants. Significant light qualities for crops differs by crops. The different physical parts are developed differently in growth stages. A representative study was performed to define growth stages physically called BBCH growth stage scale. (Boyes et al. 2001) The scale assigns a numerical value (0-9) to 10 principal developmental stages that occur in plant development: 0, germination, sprouting; 1, leaf development; 2, formation of side shoots; 3, stem elongation-rosette growth; 4, vegetative plant parts; 5, inflorescence emergence; 6, flowering; 7, fruit development; 8, ripening; 9, senescence (Fig. 4). This is considered as a framework to define growth stages of crops. Accordingly, several authors have used this framework to introduce other species of crops. (Meier et al. 2009)

Stage	Description
0	Germination / sprouting / bud development
1	Leaf development (main shoot)
2	Formation of side shoots / tillering
3	Stem elongation or rosette growth / shoot development (main shoot)
4	Development of harvestable vegetative plant parts or vegetatively propagated organs / booting (main shoot)
5	Inflorescence emergence (main shoot) / heading
6	Flowering (main shoot)
7	Development of fruit
8	Ripening or maturity of fruit and seed
9	Senescence, beginning of dormancy

**Fig. 4 Principal growth stages of plants.**

However, growth stages of basil has not been defined using this framework. In this study, plant growth level is defined until harvesting, that is the edible stage. Therefore, the stages were partitioned into three stages and the boundary between two stages was determined using the stated phenotypic characteristics of growth stages in Figs. 5 and 6.

Numeric code	Growth stage description
<b>0</b>	<b>Germination; sprouting.</b>
00	Dry seed.
01	Seed imbibition begins.
03	Seed imbibition complete.
05	Radicle emerged from seed.
06	Elongation of radicle, formation of root hairs or lateral roots.
07	Coleoptile emerged; hypocotyls with cotyledons broken through seed coat.
08	Hypocotyl with cotyledons grow toward soil surface.
09	Cotyledons or coleoptile breaks through soil surface.
<b>1</b>	<b>Leaf development (main shoot).</b>
10	First true leaf emerged from coleoptile; or cotyledons completely unfolded.
11	First true leaf.
12	Two true leaves.
13	Three true leaves, etc.
19	Nine or more true leaves (if tillering or shoot and stem elongation occur at an earlier stage or not at all, continue with either stage 21 or 31).
<b>2</b>	<b>Formation of side shoots or tillering.</b>
21	First side shoot or tiller visible.
22	Two or more side shoots or tillers visible.
23	Three or more side shoots or tillers visible, etc., to 28.
29	Nine or more side shoots or tillers visible.
<b>3</b>	<b>Stem elongation or rosette growth (main shoot; shoot development).</b>
31	Stem (rosette) 10% of final length (diameter) or 1 nodes detectable.
32	Stem (rosette) 20% of final length (diameter) or 2 nodes detectable.
33	Stem (rosette) 30% of final length (diameter) or 3 nodes detectable, etc., to 38.
39	Maximum stem length or rosette diameter reached; 9 or more nodes visible.
<b>4</b>	<b>Development of harvestable vegetative plant parts.</b>
41	Harvestable vegetative plant parts begin to develop or flag leaf sheath extending.
43	Harvestable vegetative plant parts have reached 30% of final size; or flag leaf sheath just visibly swollen.
45	Harvestable vegetative plant parts have reached 50% of final size; or flag leaf sheath swollen.

**Fig. 5 Phenotypic characteristics of each stage of plant growth according to BBCH Growth Scale (1).**

*Continued*

Numeric code	Growth stage description
47	Harvestable vegetative plant parts reach 70% of final size; or flag leaf sheath opening.
49	Harvestable vegetative plant parts reach final size; or first awns visible.
<b>5</b>	<b>Inflorescence emergence (main shoot); ear or panicle emergence.</b>
51	Inflorescence or flower buds visible.
55	First individual (closed) flowers visible.
59	First flower petals visible; or inflorescence fully emerged.
<b>6</b>	<b>Flowering on main shoot.</b>
61	Beginning of flowering: 10% flowers open.
63	30% Flowers open.
65	50% Flowers open; first petals fallen or dry.
67	Flowering finishing; majority of petals fallen or dry.
69	End of flowering; fruit set visible.
<b>7</b>	<b>Development of fruit.</b>
71	Small fruits visible or fruit has reached 10% of final size.
73	First fruits have reached final size or fruit has reached 30% of final size.
75	50% Fruits have reached final size or fruit has reached 50% of normal size.
77	70% Fruits have reached final size or fruit has reached 70% of normal size.
79	Nearly all fruits have reached final size.
<b>8</b>	<b>Ripening or maturity of fruit and seed.</b>
81	Beginning of ripening or fruit coloration.
85	Advanced ripening or fruit coloration.
87	Fruit begins to soften.
89	Fully ripe; beginning of fruit abscission.
<b>9</b>	<b>Senescence: beginning of dormancy.</b>
91	Shoot development completed; foliage still green.
93	Leaves begin to change color or fall.
95	50% Leaves discolored or fallen.
97	Plant material dead or dormant.
99	Harvested seed.

**Fig. 6 Phenotypic characteristics of each stage of plant growth according to BBCH Growth Scale (2).**

### **1.2.6. Fuzzy Logic Control Systems in Agriculture**

Fuzzy logic has been used in appliances such as electric rice cookers and air conditioners because its concept is free from the binary approach. Fuzzy logic records the degree of validity. In fuzzy systems, contrary to fuzzy logic, crisp logic is the same as boolean logic; either 0 or 1. In contrast, fuzzy logic is continuous valued, has membership functions and considers the degree of membership.

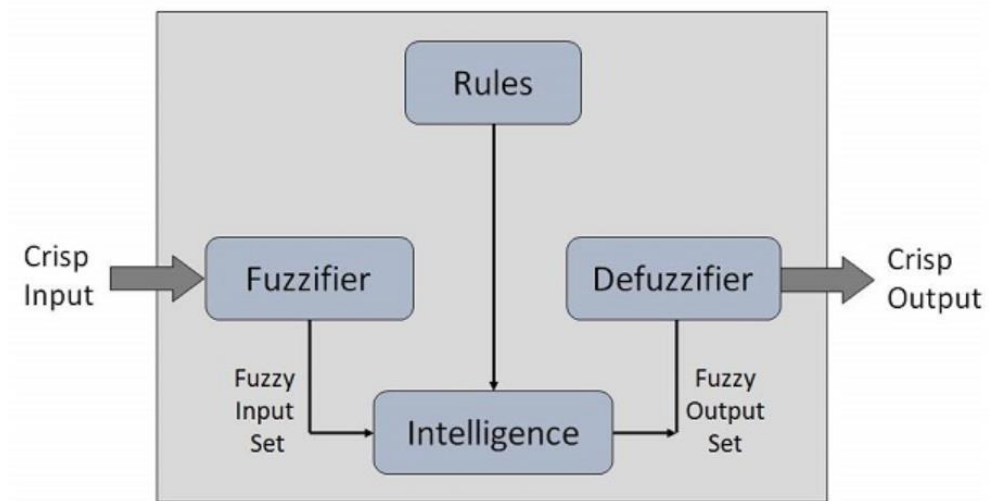
Fuzzy logic is effective in feedback control systems and easier to implement. The computational structure of fuzzy logic is composed of fuzzification, inference engine and defuzzification modules (Fig. 7).

For example, fuzzification translates the numerical values for error in temperature into a linguistic value such as ‘low’, ‘very low’, ‘zero’, ‘high’, and ‘very high’. A fuzzy inference engine infers fuzzy outputs using fuzzy implications and the rules of inference of fuzzy logic. Defuzzification uses the fuzzy output of the rules and to generate an output formulated in the form of ‘crisp’ numeric value used as control input to plant. The relation between input and output is in the form of ‘If-Then’ rules, that are based on dynamic performance of process (Potdar, Patil, and Ramchandra Mudholkar 2017).

Managing environmental conditions for greenhouse is performed using fuzzy logic in agriculture. (Bannerjee et al. 2018; Daud, Handika, and Bintoro 2018; Dengel 2013; Iliev, Sazdov, and Zakeri 2012; Lakhiar et al. 2018; Revathi and Sivakumaran 2016; Robles Algarín, Callejas Cabarcas,

and Polo Llanos 2017; Xu et al. 2016)

However, studies on applying fuzzy logic in managing light quality in plants' growth stages to harvest is scarce. There is no proposed method of modification to examine the vulnerable components of a designed fuzzy logic.



**Fig. 7 Configuration of FLC. (Artificial Intelligence - Fuzzy Logic Systems - Tutorialspoint n.d.)**

### **1.3. Research Purpose and Significance**

#### **1.3.1. Research objectives**

This study is aimed at achieving the following objectives.

- To develop an automatical control of light quality for cultivation with fuzzy logic system in growth stages of crops partitioned into three stages (Germination, Vegetative growth, and Flowering).
- To manage environment factors such as temperature and humidity for growing basil at home at low cost.
- To investigate the difference between outer and inner environment (temperature, humidity) of the controlling system.
- To determine significant factors to be considered as a household appliances for cultivating herb basil.
- To assess fuzzy logic system with Pearson's correlation coefficients and comparison between simulation and actual operation.

### **1.3.2. Significance**

For lighting, most researchers have performed cultivation with consistent light quality in the entire stages of plant growth. This study adjusts light quality optimally in the plant growth stages to enhance the quality of crops.

Furthermore, this study defines the growth levels of basil based on phenotype and automatically determines the duration, sets the optimal environmental conditions, as the initial experiment in this. The success of this experiment indicates significantly minimizing labor systems requiring less knowledge of growers. The search for high quality crops will reduce.

Finally, determining weaknesses of the system by Pearson's correlation coefficients is a novel method of assessment for fuzzy logic control. Most fuzzy logic control systems use human's subjective standards. Only results related to setting the operating system to set points are indicative of well-organized systems. There is no proposed method to address the failing system. To receive feedbacks for adjustment of the fuzzy logic, this study adopted the Pearson's correlation coefficients because the variables of input and output are associated with each other in the fuzzy logic. This method shows the drawbacks in the system's rules and membership functions. Therefore, fuzzy logic control systems can be modified and enhanced.

## **Chapter 2. Materials and Methods**

### **2.1. Preliminary Performance Test of Conventional Control System**

#### **2.1.1. Purpose of Preliminary Test**

The following are the requirements prior to developing the proposed system.

- Purchasing the various devices and respectively performing the performance tests to select suitable devices for this study.
- Some designs for household should be developed as trials to determine the design can be effective and efficient to operate in homes and to determine suitable locations for devices in the frame of each design.
- To develop a circuit for this system to reduce trials and errors.
- To simulate the fuzzy logic system independently to examine its accuracy and operation methods.

## **2.1.2. Hardware Design**

### **2.1.2.1. Wall-mount and standing type (two ways)**

Because this study considers development of gardening cultivator for home use, the product design should be modern and favorable for urban use. Furthermore, practicality is an utmost priority.

Therefore, wall was considered for a gardening spaces because it is predominantly unused and abandoned. Although wall is usually the space for paintings, it can be used to support green life because it has lighting system and offers optimal environment to plants. To maximize the practical use, this product is developed based on two concepts; as standing and wall-mount in one design.



**Fig. 8 Each separated parts of a prototype for the wall-mount type.**

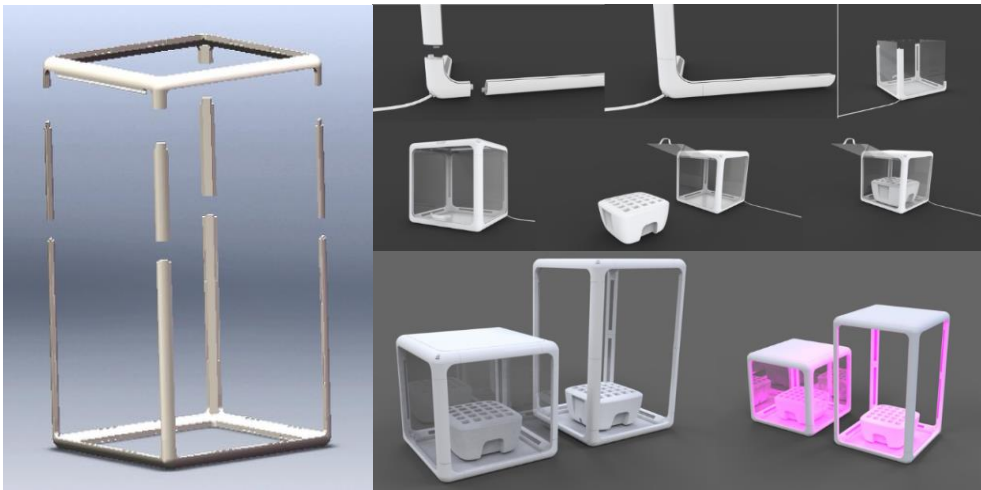
*There are four pots and the right bottom pot is excluded.*



**Fig. 9 Two types (Standing and Wall-mount) in one design.**

### 2.1.2.2. Modular type

Crops grow to varying heights, thus the size of the controlled environment system should be flexibly adjusted as plants grow. Available spaces vary with users; some prefer larger sizes, and others prefer smaller sizes. To address these problems, the modular type was selected. This type can be adjusted by adding or removing modules depending on user preferences. The LEDs are installed on the sides to be consistent with that of Joshi *et al.*



**Fig. 10** Modular type with adjustable height and width to fit the available space.



**Fig. 11** Images of positions of the prototype at home.

### **2.1.3. Hardware Operating Test With Arduino**

#### **2.1.3.1. Materials**

The materials were selected based on the Arduino system. (Fig. 12) For the wall-mount and modular types, most components were used identically except for mist kit including water tank and peltier module applied fan.

However, in this experiment, the modular type cultivator was selected because wall-mount design was small to be equipped with peltier module applied fan.

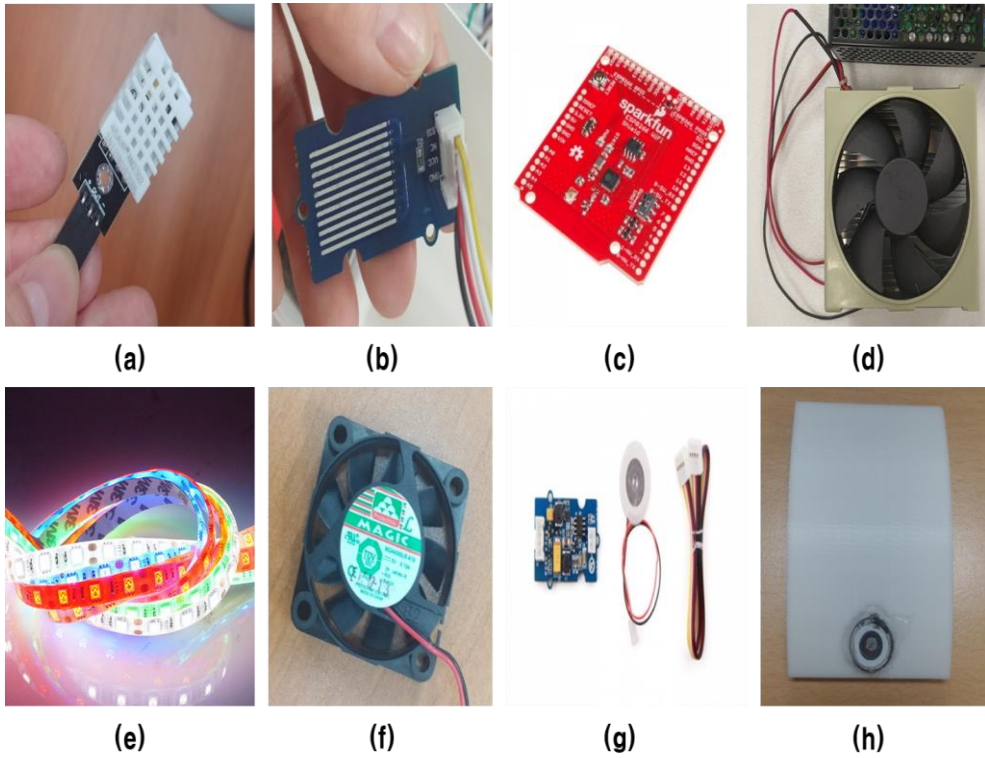
Although the wall-mount type did not have a peltier-applied fan, it had a humidifying function through the mist generator, that the modular type did not have. In the wall-mount type, the system controls humidity and temperature by operating a fan and a mist, whereas it was controlled by peltier-applied fan in modular type control system.

To fix the water tank to the wall-mount frame, it was three dimensionally printed and ultrasonic mist generator module was used. Glue gun was used to prevent from leakages from the boundary.

Additionally, the Arduino was connected to the internet wirelessly using Arduino WiFi Shield.

For water status, a water alarming function to examine the water levels was adopted.

LEDs lightening up with independent three lights were selected to manage the light quality and intensity.



**Fig. 12 Final control parts.**

(a) Humidity and Temperature sensor (AM2302); (b) Water-level sensor (Grove arduino 5V); (c) Arduino Wi-fi shield (ESP8266); (d) Peltier module applied fan (Self-production); (e) LED (RGB); (f) Cooling fan (2510, 5V); (g) Mist kit (Grove); (h) Water tank for mist.(Self-production)

### 2.1.3.2. Overall system

The entire system was developed with sensors and actuators. (Fig. 13) Monitoring and controlling systems are set up.

Through monitoring, values of temperature and humidity were recorded to examine the air conditions and water-level to identify water shortage.

In the controlling system, lighting system and air system were developed. In particular, lighting system was adjusted in a dimension of light quality controlling red, green, and blue lights with manually fixed ratio per growth level. Besides, a peltier-applied fan performing heating, cooling, and ventilating system.

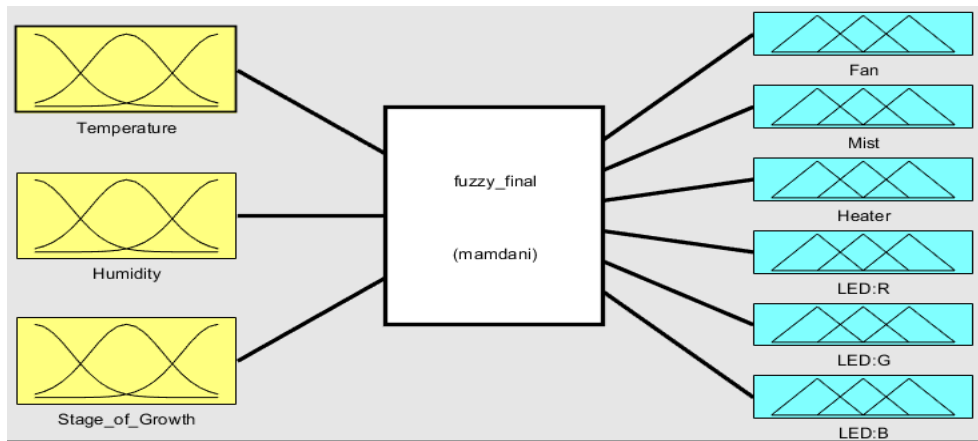
Nebulization system was not installed because this is a small-scale hydroponic system. A hydroponic system in a small space will increase the humidity. The fan-using ventilation was adequate to manage the humidity although not using a mist function.



**Fig. 13 The modular type working by mobile application manually selecting plant growth stages.**

#### 2.1.4. Fuzzy Logic Simulation With MATLAB and Arduino

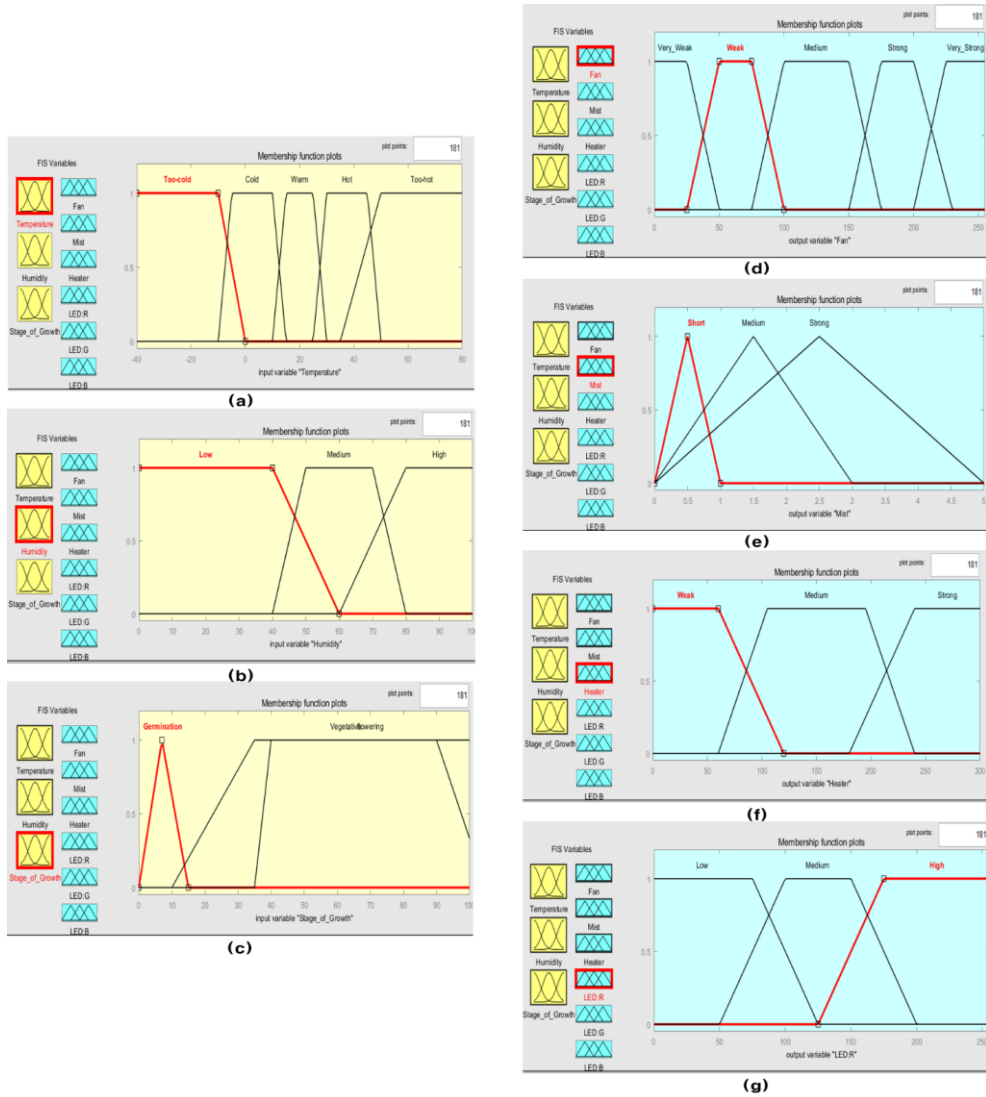
MATLAB was used as a programming language to set the fuzzy logic system. Input and output variables were designated with its different membership functions based on its features as Mamdani. Three input variables (Temperature, Humidity, and growth stages) and six output variables (fan, mist, heater, red light, green light, and blue light) were fixed. To adjust the light quality and quantity, the light was partitioned into three different wavelengths.



**Fig. 14 Fuzzy logic (Mamdani).**

*Three input and six output variables*

This experiment performed to set the rules and membership functions based on information from references. Sweet basil was the target plant for this system. The detailed standards and numbers is shown in Fig. 15.



**Fig. 15 Variables and Membership functions.**

*Input variables : (a) Temperature; (b) Relative Humidity; (c) Growth stages.*

*Output variables : (d) Fan; (e) Mist; (f) Heater; (g) LED(R,G,B each)*

There were eleven rules to adjust the figures in the system.

1. IF (Temperature is Too-cold) THEN (Fan is Very\_Strong) and (Heater is Medium).
2. IF (Temperature is Cold) THEN (Fan is Strong) and (Heater is Weak).
3. IF (Temperature is Warm) and (Humidity is Medium) THEN (Fan is Medium) and (Mist is Short).
4. IF (Temperature is Hot) and (Humidity is Medium) THEN (Fan is Strong) and (Mist is Medium).
5. IF (Temperature is Too-hot) and (Humidity is Medium) THEN (Fan is Very\_Strong) and (Mist is Strong).
6. IF (Humidity is Low) THEN (Fan is Very\_Weak) and (Mist is Strong).
7. IF (Humidity is Medium) THEN (Fan is Weak) and (Mist is Short).
8. IF (Humidity is High) THEN (Fan is Very\_Strong).
9. IF (Stage\_of\_Growth is Germination) THEN (LED:R is High) and (LED:G is High) and (LED:B is High).
10. IF (Stage\_of\_Growth is Vegetative) THEN (LED:R is High) and (LED:G is Low) and (LED:B is Medium).
11. IF (Stage\_of\_Growth is flowering) THEN (LED:R is High) and (LED:G is Low) and (LED:B is Low).

## **2.2. Experimental Hardware Setup and Configuration**

### **2.2.1. Materials**

The materials for this study are shown in Fig. 16.

In this test, the wall-mount design was selected to minimize the space for indoor cultivation.

Also, Raspberry pi 4, the current model, was selected to process the system because nearly-real-time-based data would be saved and accumulated from a camera, sensors and computing program. To manage such big data and maintain system rapidly, Raspberry Pi was the optimal choice for the long term. Besides, it enables additional complicated applications. A pi Touchscreen display was connected to Raspberry pi with a standing case for convenience for the programming.

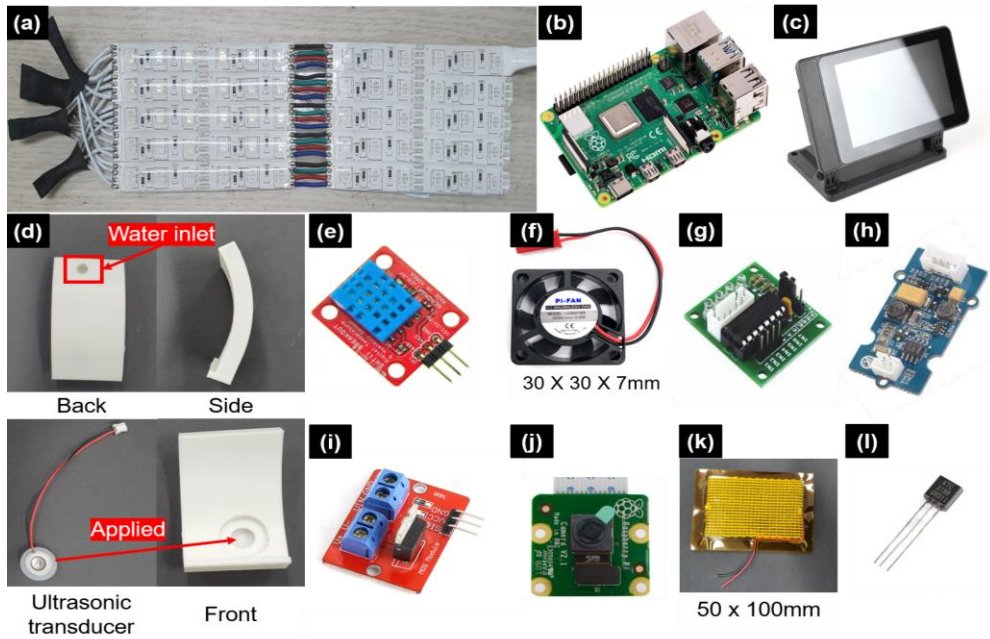
To monitor and regulate humidity and temperature, DHT11 positioned in the upper left side (Fig. 17) recorded inner humidity and temperature every minute. These values determined the output variables' activation; fan, mist and heaters. For comparison, additional DHT11 was attached to the outer side of the cultivator to record the temperature and humidity of the indoor side. An ultrasonic mist generator attached to the three dimensionally printed water tank was installed. A fan was located in upper right side and a mist was fixed to the top of the fan. Additionally, two heaters were attached inside to both pillars to add heating to the air evenly.

To monitor the operation status and growing plants, a camera was fixed to the middle of the top to be used as a monitor and also taking pictures every

six hours.

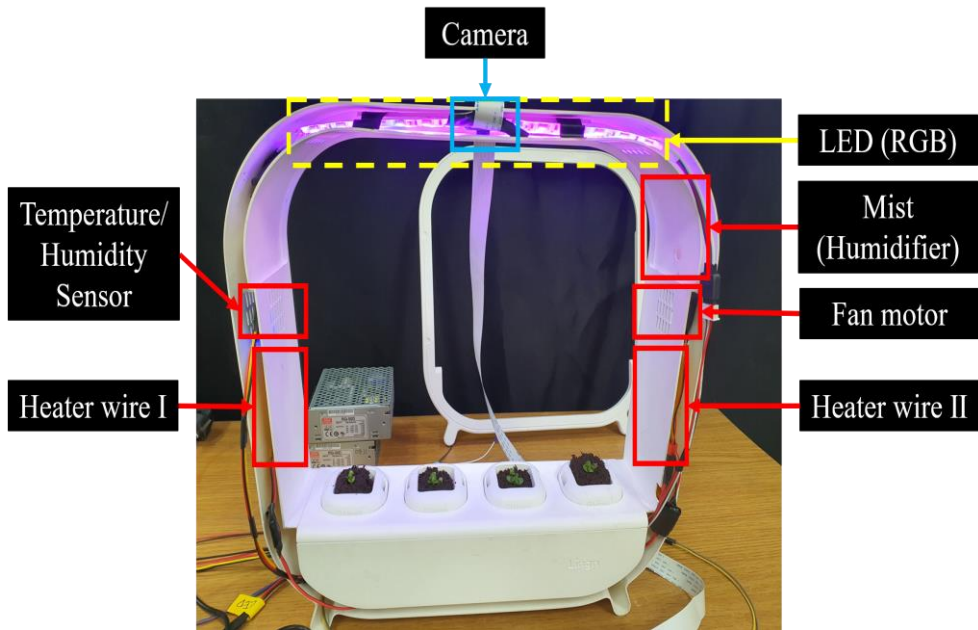
There were limitations in voltage and signal input. Particularly, Raspberry Pi had rails for loading low voltages of 3.3 V and 5 V, and devices such as heaters and fan motors had only two connection lines for the ground and 5 V, that they could not be regulated at a signal.

To address these problems, several supplemental modules were required to load higher voltages from external power supply. (Fig. 18) A ULN2003 stepper motor driver board was connected to high current LEDs tailored for driving three lights independently at the given signals on high-voltages of 12 V. IRF520 MOSFET transistors were linked to two heating wire pads because it was designed to switch heavy DC loads from a single digital pin of microcontroller. An NPN (Negative-Positive-Negative) transistor (C3198) was applied to the fan to control the signals.

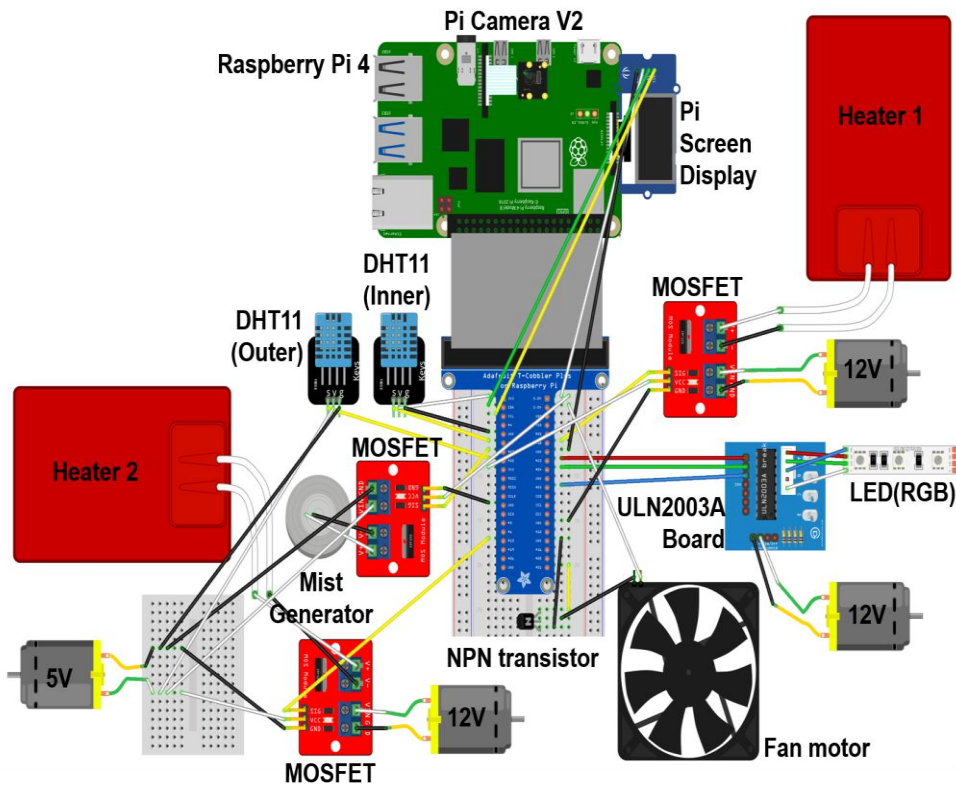


**Fig. 16 Sensors, actuators and other components used in the experiment.**

(a) Tailored LED (RGB); (b) Raspberry Pi4; (c) pi Touchscreen display and Standing case; (d) Water tank and Ultrasonic mist generator; (e) DHT11 sensing temperature and humidity; (f) Fan motor; (g) ULN2003 stepper motor driver board for controlling LED; (h) Mist control module (Grove water atomization); (i) IRF520 MOSFET driver module for controlling heating wire pads; (j) Pi camera module V2; (k) Heating wire pad; (l) NPN transistor(C3198) for controlling a fan.



**Fig. 17** Setup with sensors and actuators in a cultivator.



**Fig. 18** Circuit schematic.

### **2.2.2. Overall circuit and system setup**

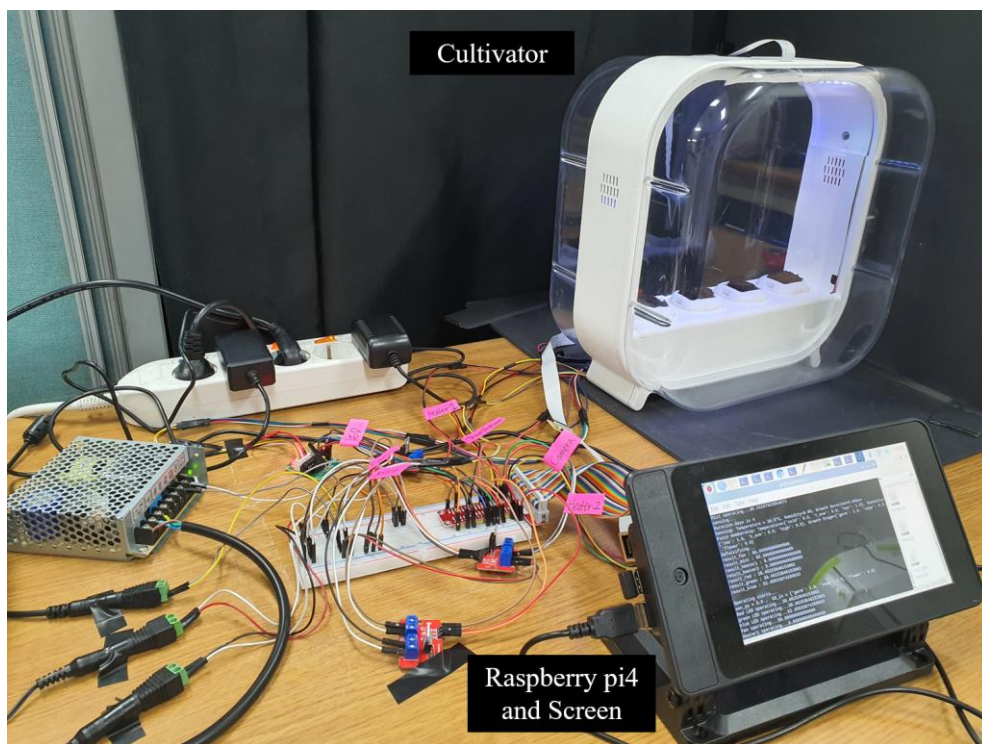
As external power supply, three AC/DC adapters of 12 V and one SMPS for 5 V were used (Fig. 19). One AC/DC adapter drove the high current LEDs and remaining were for heaters (heater1 and heater2). The SMPS controlled the mist generator, operating DHT11 sensing external temperature and humidity, and one MOSFET module of heater2 by parallel connection. All other devices and modules were supplied with power from the Raspberry Pi's rails.

Because the camera's module ribbon cable was short to connect to the Raspberry Pi, two ribbon cable connectors were interconnected.

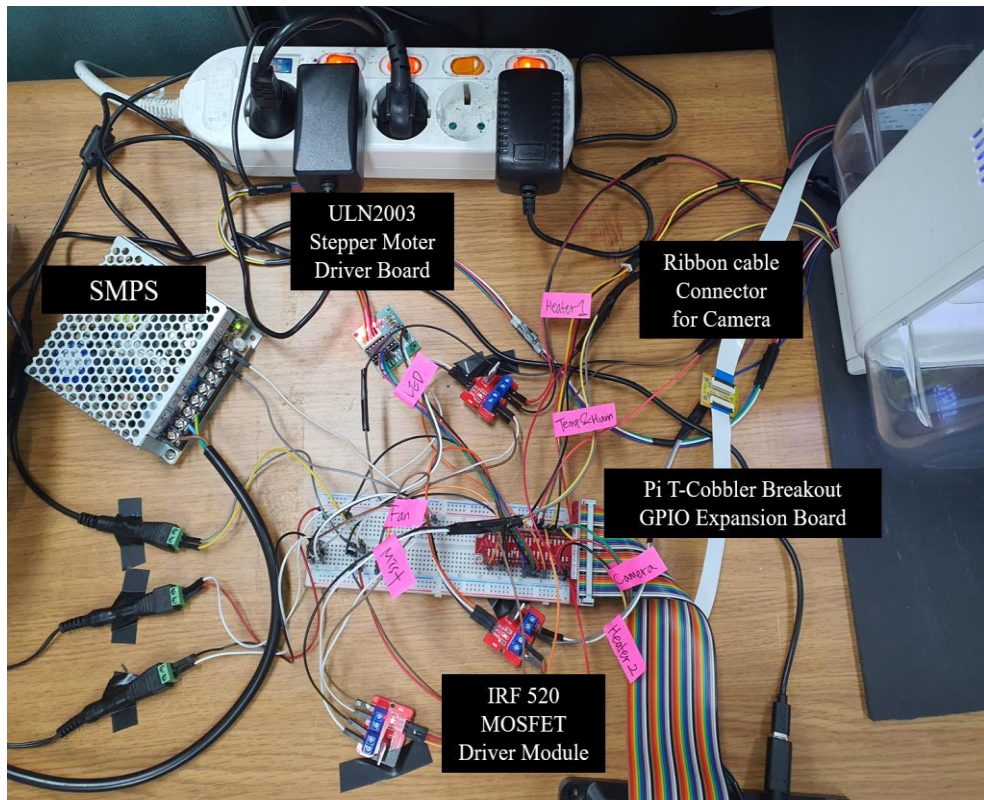
To expand the Raspberry Pi to a bread board, T-cobbler breakout GPIO expansion board was applied on the bread board.

For the structural form of the cultivator, it was closed, although not completely sealed, by twelve magnets; six in the front and six in the rear (Fig. 21). At the back, there were two holes on pillars to hang on the wall.

For hydroponics, simply water culture was used. Although air pump can be optional, no pumping device was used to minimize the price. The water was replaced once a week.



**Fig. 19 Overall system; Raspberry Pi 4, circuit and a controlled cultivator.**



**Fig. 20 Circuit**



**Fig. 21 Cultivator's structural form.**

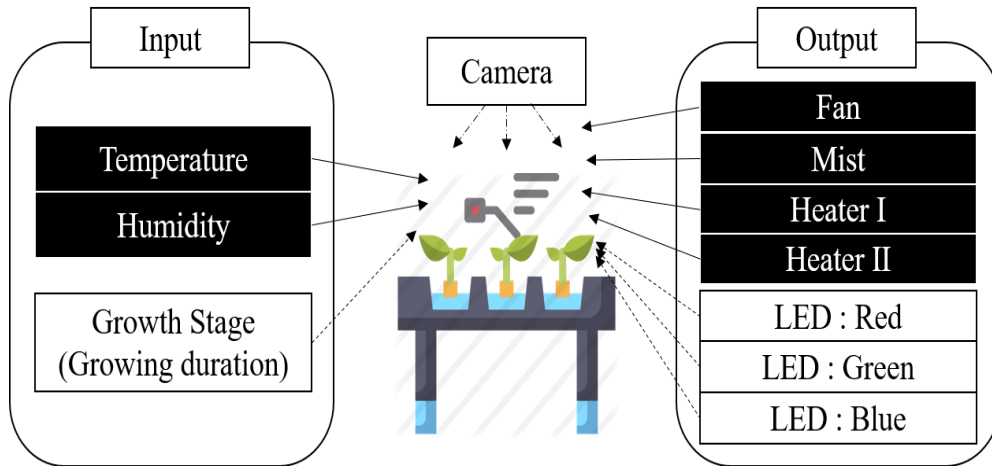
### **2.2.3. Fuzzy logic control system**

The environmental conditions were managed for defuzzification using fuzzy logic. Using Python, the fuzzy-logic control system was developed. Python was selected as a coding language for possibility to enable adding other artificial intelligence technology in further study because Python is a common programming language in the field of AI.

The Fuzzy logic was designed with Mamdani inference and centroid of defuzzification. Also, it was designated with three input parameters (Temperature, Humidity, and Growth stages) and seven output variables (fan, mist, heater1, heater2, Red, Green, Blue light). These can be partitioned into two groups (Fig. 22).

Group 1 managed inner temperature and humidity. When their values were input into the system every minute, fan, mist, heater1 and heater2 were activated upon defuzzified outputs. Thus, Group 1 comprised of temperature, humidity, fan, mist, heater1 and heater2.

Group 2 managed the lights. Light quality and intensity were controlled in growth stages. In the growth, red, green, blue lights were adjusted according to the computed values. Therefore, Group 2 consisted of growth stage, red, green, and blue.



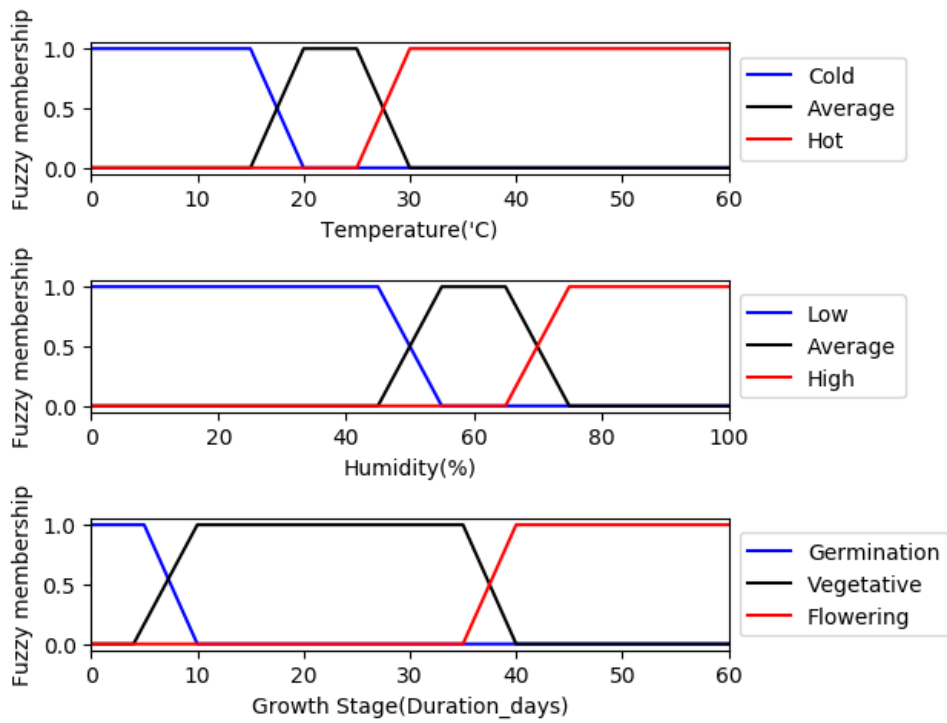
**Fig. 22 The fuzzy control system including input and output variables.**

Because this was the first integrated system of hardware and software, membership functions were partitioned into three components to minimize complexity.

The temperature's x-axis was in degree Celcius and humidity is in percent. Growth stage's was equally spaced day of time intervals as duration.

Because all membership functions were designed based on the requirements for basil cultivation, the system identified a temperature of 20 – 25 °C and humidity of 55 – 65 % as average. (Fig. 23)

Also, because germination periods are different by seeds, germination in growth stages was arranged in five to seven days. Although the flowering stage depends on the cultivator's management, it begins from the 30<sup>th</sup> day, whereas vegetative stage begins to descend at the same time.



**Fig. 23 Membership functions of input parameters.**

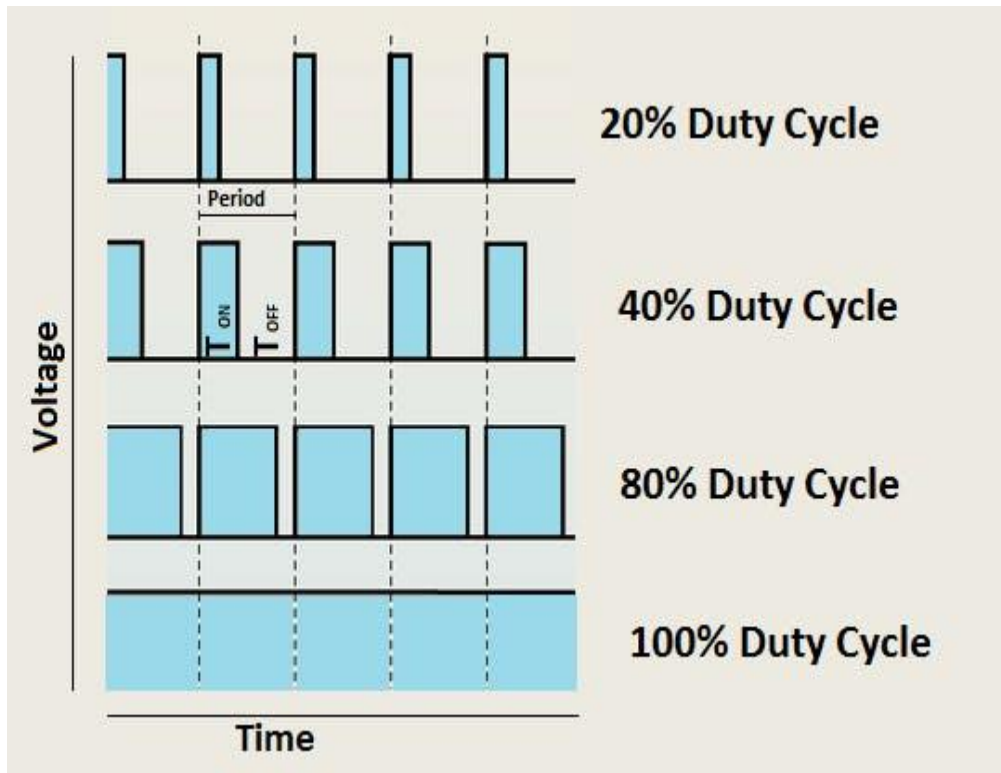
To control the degree of devices' operations such as brightness of LED, PWM (Pulse Width Modulation) was used. It is used to produce analog output with digital means.

PWM uses a square pulse wave whose pulse width is modulated leading to the variation of the average value of the waveform. The average value of the signal ( $\bar{y}$ ) directly depends on the duty cycle. Duty cycle is the proportion of 'HIGH' time to regular interval or 'period' of time. It is expressed as a percentage of 'on' time. The lower duty cycle yields lower power so that the power stays 'off' for most time (Fig. 24).

If the waveform is  $f(t)$  with period  $T$ , a low value  $y_{min}$ , a high value  $y_{max}$ , and a duty cycle  $D$ , then:

$$\begin{aligned}\bar{y} &= \frac{1}{T} \int_0^T f(t) dt \\ \bar{y} &= \frac{1}{T} \left( \int_0^{DT} y_{max} dt + \int_{DT}^T y_{min} dt \right) \\ &= \frac{1}{T} (D \cdot T \cdot y_{max} + T(1 - D)y_{min}) \\ &= D \cdot y_{max} + (1 - D)y_{min}\end{aligned}$$

Because all the output variables were used together with analog output, the x-axes were ranged from zero to 100% on the basis of duty cycles.



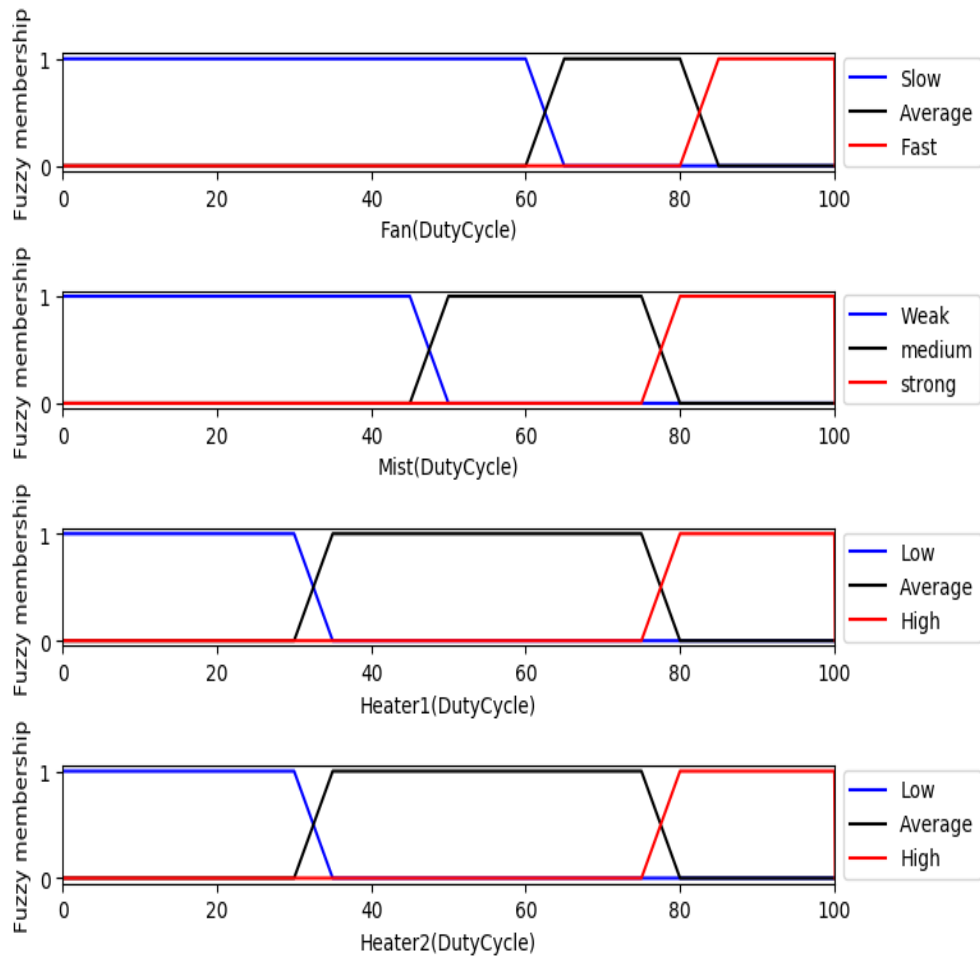
**Fig. 24 The duty cycle. (Arduino PWM Tutorial - Arduino Project Hub n.d.)**

For fan, its basic power was higher than that of any other device because fan was used for ventilation and managing temperature and humidity.

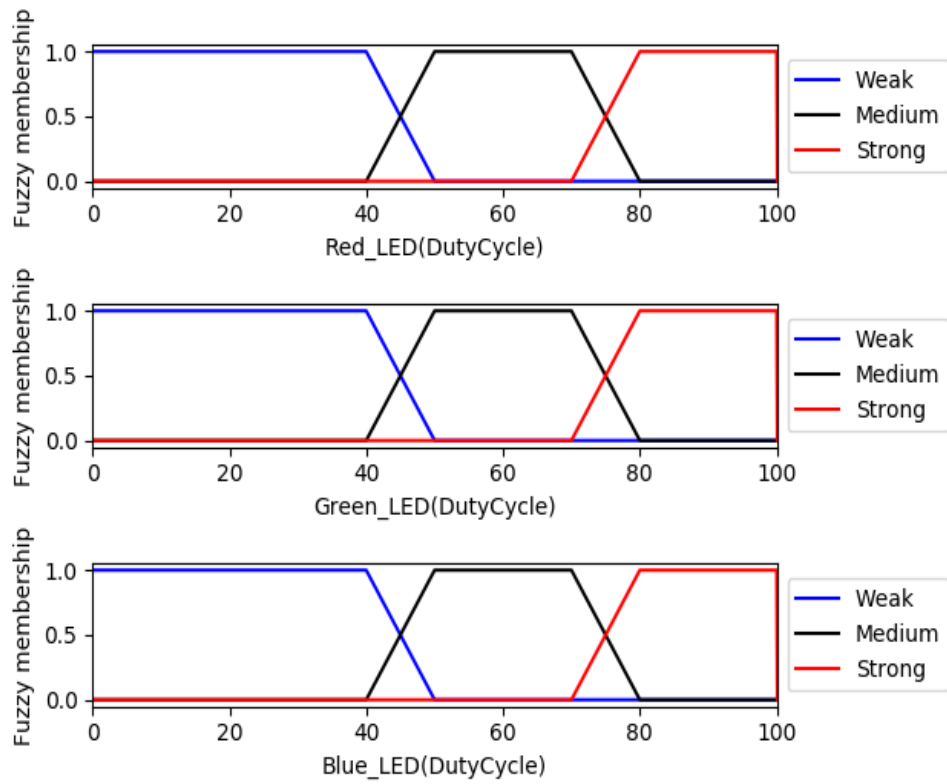
It is difficult to set the membership functions using mist because its fogging rate could not be measured using numbers. Furthermore, examining quantities of fogging with the eye in different duty cycles can yield inaccurate results.

Heaters' outputs were 70 °C and 63 °C with an average of 66.5 °C. Therefore, 1 % of duty cycle was considered as 0.665 °C. Consequently, the peak of average was 30 which was 19.95 °C and the highest value was 80 operating up to 53.2 °C to rapidly increase the temperature considering that

all values were reset and recalculated every minute.



**Fig. 25** Membership functions of output variables (1).



**Fig. 26** Membership functions of output variables (2).

For Group 1, from rule 1 to rule 3, if it was cold or under high humidity, the fan and heater were fast and strong to spread the heat rapidly. Simultaneously, mist operated to prevent becoming dry and colder. All devices operated at average rate if the temperature and humidity were in average.

Rule 4 to rule 6 support lighting control. Blue light affected germination and vegetative growth stage dominantly. Because germinating seeds require darker spaces, blue light was medium and others were weak. Vegetative growth, it requires adequate light so blue was strong and the others were medium. In flowering stage, red light should be intensively shed on plants, so red was strong.

The rules are described as follows:

1. IF (Temperature is Hot) or (Humidity is Low) THEN (Fan is Average) and (Mist is Strong) and (Heater1 is Low) and (Heater2 is Low).
2. IF (Temperature is Average) or (Humidity is Average) THEN (Fan is Slow) and (Mist is Medium) and (Heater1 is Average) and (Heater2 is Average).
3. IF (Temperature is Cold) or (Humidity is High) THEN (Fan is Fast) and (Mist is Weak) and (Heater1 is High) and (Heater2 is High).
4. IF (Growth Stage is Germination) THEN (Red is Weak) and (Blue is Medium) and (Green is Weak).
5. IF (Growth Stage is Vegetative) THEN (Red is Medium) and (Blue is Strong) and (Green is Medium).
6. IF (Growth Stage is Flowering) THEN (Red is Strong) and (Blue is Weak) and (Green is Strong).

Lastly, whole designed fuzzy logic control system had been simulated by MATLAB to gain rule view and surface view before actual operation.

**Table 1. Fuzzy associative matrix (Group 1).**

Humidity Temperature	Low	Average	High
Cold			FF MW HH
Average		FA MM HA	
Hot	FS MS HL		

**Table 2. Fuzzy associative matrix (Group 2).**

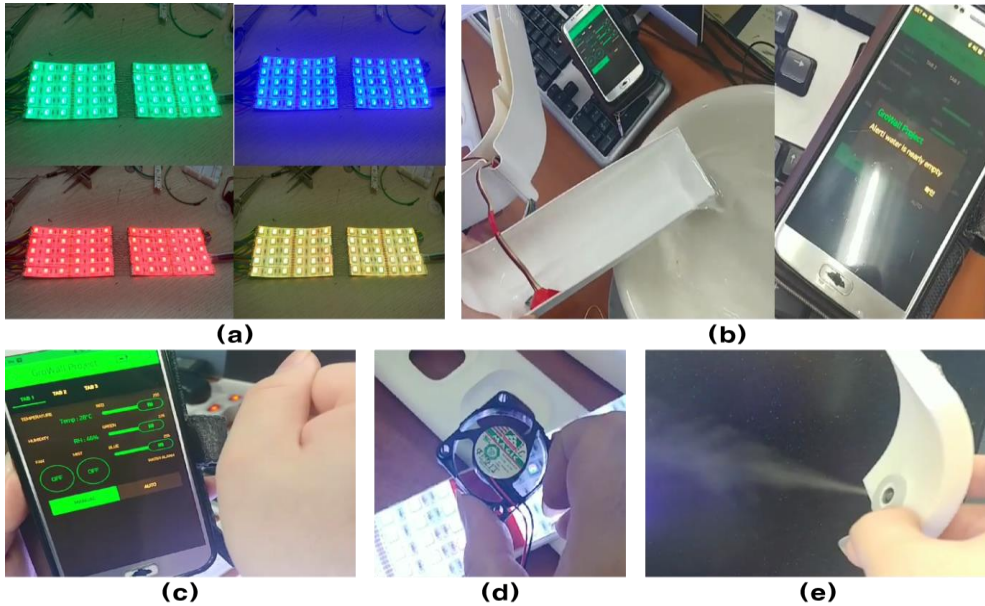
Growth Stage	Red	Green	Blue
Germination	Weak	Weak	Medium
Vegetative	Medium	Medium	Strong
Flowering	Strong	Strong	Weak

## Chapter 3. Results and Discussion

### 3.1. Preliminary Test Results

#### 3.1.1. Hardware work

Lighting was able to be adjusted resulting in cultivating crops with different light quality and quantity by using mobile application named Blync. Also, if the water level reduced, the mobile alarmed immediately. The humidity and temperature sensor values increased with holding the sensor. Fan and mist were efficient as targeted functions. The Peltier applied fan operated suitably as cooling, heating and fanning. Although the devices were fixed on a modular type frame, all components performed their functions without problems.



**Fig. 27 Operations of components.**

(a) LED (G,B,R,Y); (b) Water level alarm; (c) Temperature and Relative Humidity monitoring; (d) Fan; (e) Mist.

### 3.1.2. Software work

If manually targeted values of temperature, humidity, and growth were used as inputs; 20 of temperature, 41.6 of humidity, and 50 of growth and the system identified this condition as warm temperature, almost low although considerably medium humidity, the boarder of vegetative and flowering stages, the fan performed significantly weak and the mist operation was significantly strong. Also, heat was not operated and red light was high whereas green and blue light was low. As set by coding, the system performed optimally.

```
-> Entrance:
-> Temperature: 20.00, Humidity: 41.60, and Growth: 50.00
-> Input:
-> Temperature: TooCold-> 0.00, Cold-> 0.00, Warm-> 1.00, Hot-> 0.00, TooHot-> 0.00
-> Humidity: Low-> 0.92, Medium-> 0.16, High-> 0.00
-> Growth: Germination-> 0.00, Vegetative-> 1.00, Flowering-> 1.00
->
->
-> Output:
-> Fan: VeryWeak-> 0.92, Weak-> 0.16, Medium-> 0.16, Strong-> 0.00, VeryStrong-> 0.00
-> Mist: Short-> 0.16, Medium-> 0.00, Strong-> 0.92
-> Heat: Weak-> 0.00, Medium-> 0.00, Strong-> 0.00
-> LRed: Low-> 0.00, Medium-> 0.00, High-> 1.00
-> LGreen: Low-> 1.00, Medium-> 0.00, High-> 0.00
-> LBlue: Low-> 1.00, Medium-> 1.00, High-> 0.00
->
->
-> Result:
-> Fan: 51.76, Mist: 2.39, and Heater: 0.00      LedR: 201.51, LedG: 51.04, and LedB: 88.11
```

**Fig. 28 Setting values and its result.**

*Setting values : 20 of Temperature, 41.6 of Humidity, 50 of Growth*

### **3.1.3. Limitation**

The preliminary experiment installing devices directly on the frame and examining the software simultaneously. Because the experiment was successful, it was applied in practical situation by cultivating plants with this system to investigate if this well-structured system enhances plant growth.

A limitation was that the hardware and software were not merged into one system. Hardware operated upon manual signals. In addition, the fuzzy logic control system was simulation to investigate if it produces accurate values with input figures based on fuzzy logic, whereas not connected to the hardware. The preliminary tests were achieved independently. Therefore, it must be integrated as one system. That is, the hardware should be setup and operated appropriately and automatically based on the intentionally designed fuzzy logic control system.

A mist generator was excluded in the system although it was essential to adjust humidity. Excluding the humidifier based on the assumption that hydroponic system will increase the humidity was inaccurate.

## **3.2. Experimental results**

### **3.2.1. Simulation**

#### **3.2.1.1. Rule view**

To check if the rules are applicated right, simulation was conducted through MATLAB. (Fig. 29)

The first test was set with values of 18, 69, and 36 on temperature, humidity, and growth stage each. According to membership functions, (Temperature is Cold / Average) and (Humidity is Average / High) and (Growth Stage is Vegetative / Flowering) were applied. It means that Rule 2, 3, 5, 6 were carried out.

In the process, fuzzy results were drawn. (Temperature is Cold) = 0.4, (Temperature is Average) = 0.6, (Humidity is Average) = 0.6, (Humidity is High) = 0.4, (Growth Stage is Vegetative) = 0.9, (Growth Stage is Flowering) = 0.2.

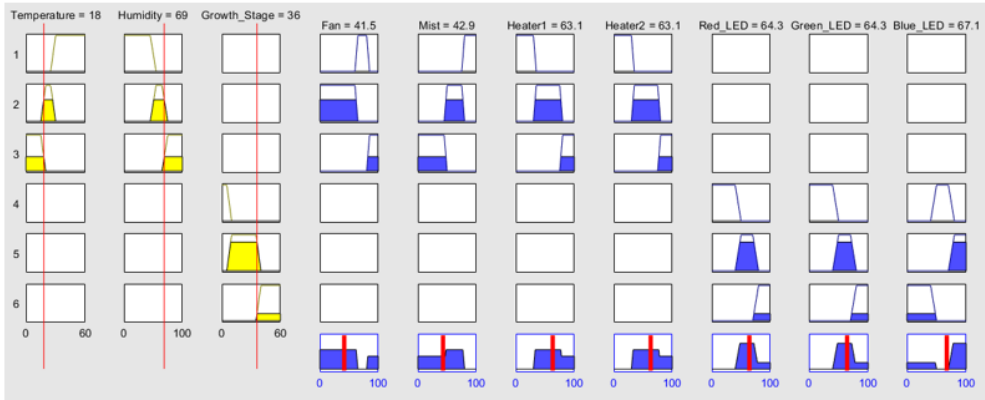
With these fuzzy results, clipping was done to membership functions of output variables, and then the clipped results were aggregated to be defuzzified. Defuzzified values were calculated by centroid technique. The final values from fuzzy logic control were 41.5 on Fan, 42.9 on Mist, 63.1 on Heater1 and Heater2, 64.3 on Red and Green LEDs, and 67.1 on Blue LED.

Along the same lines, the second test was implemented with values of 27, 48, and 7 on temperature, humidity and growth stage each. In the process, defuzzified values by centroid technique were calculated; 42.6 on

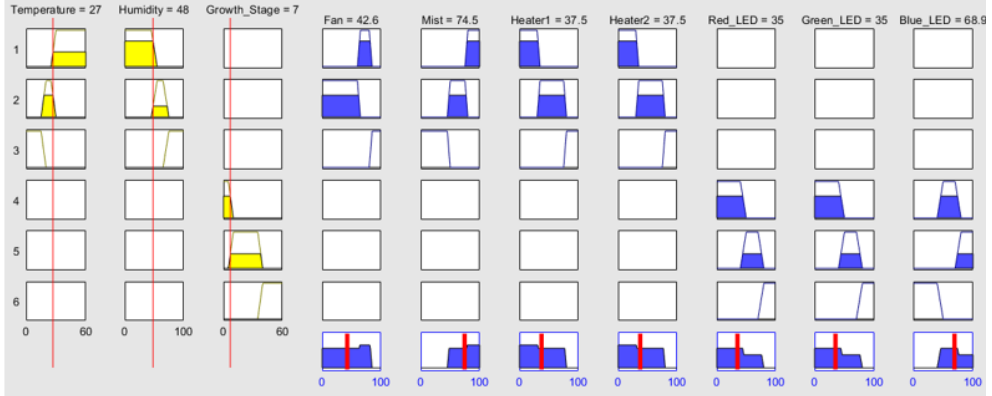
Fan, 44.7 on Mist, 46 on Heater1 and Heater2, 22.3 on Red and Green LEDs, and 60 on Blue LED.

The last test was implemented with values of 45, 53, and 27 on temperature, humidity and growth stage each. The defuzzified values by centroid technique were 36.1 on Fan, 49.9 on Mist, 59.3 on Heater1 and Heater2, 60 on Red and Green LEDs, and 87.6 on Blue LED.

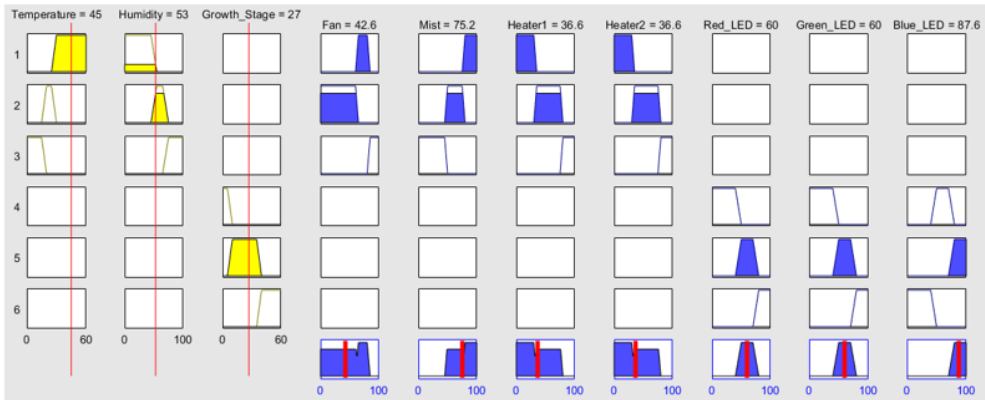
(a)



(b)



(c)



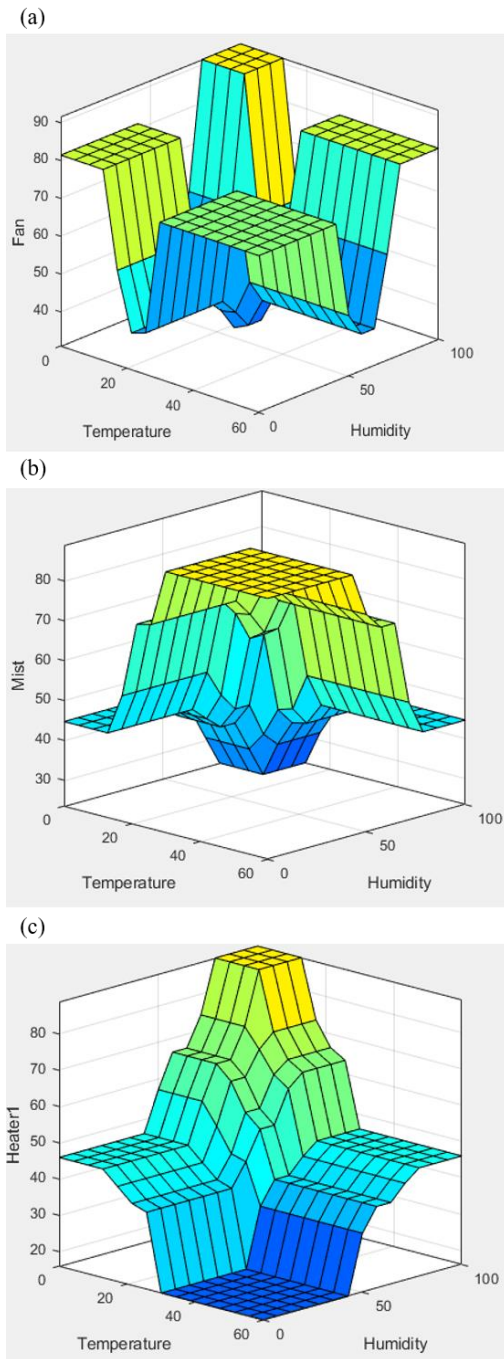
**Fig. 29 Rule View of Fuzzy Logic Simulation**

(a) *Temperature = 18, Humidity = 69, Growth Stage = 36*

(b) *Temperature = 27, Humidity = 48, Growth Stage = 7*

(c) *Temperature = 45, Humidity = 53, Growth Stage = 27*

### 3.2.1.2. Surface view



**Fig. 30 Surface View of Fuzzy Logic Simulation.**

(a) *Fan*; (b) *Mist*; (c) *Heaters*  
(*Heater1* and *Heater2*)

Fan was designed to work lowest when temperature and humidity are medium. As intentioned, the surface view showed that fan works lowest in the middle with shape of a cross.

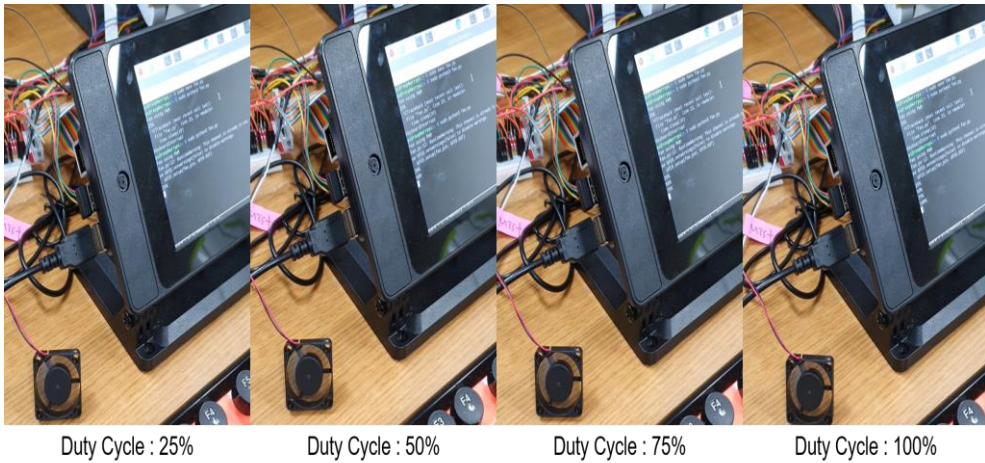
In case of Mist, it is supposed to be lower when temperature is down or humidity is high. Also, it has to be higher as temperature goes up or humidity goes down. The surface show reflected those well. Mist was lowest when temperature is lowest and humidity is highest.

Heaters were set reversely compared to humidity. The result of simulation mirrored the intention properly.

### 3.2.2. Hardware operations

#### 3.2.2.1. Fan

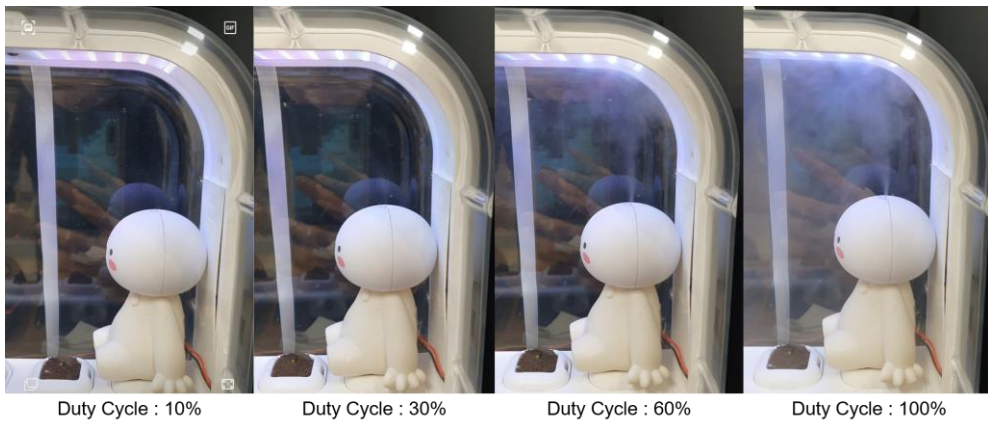
The fan motor operated appropriately according to the inputted signal of duty cycle, controlling the speed of the fan resulting in wind strength.



**Fig. 31 Fan in operation together with the numbers of duty cycle.**

#### 3.2.2.2. Mist

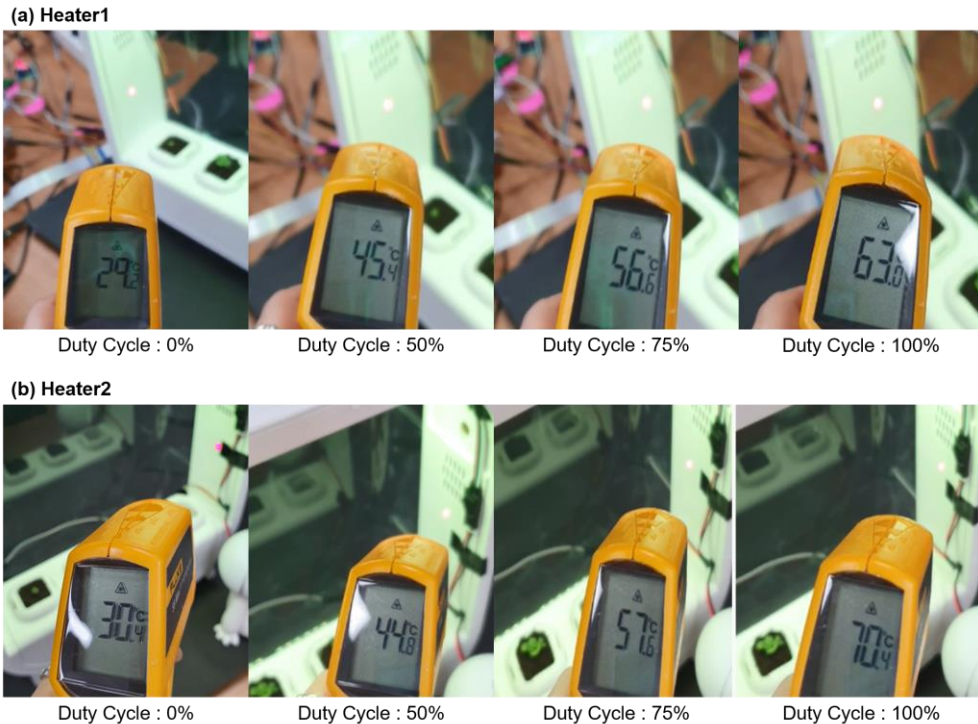
The mist generator operated appropriately according to the inputted signal of duty cycle, controlling quantity of fog resulting in humidifying.



**Fig. 32 Mist generator in operation together with the numbers of duty cycle.**

### 3.2.2.3. Heaters

The heaters operated appropriately according to the inputted signal of duty cycle, controlling heating resulting in warming the space. However, although both heaters were the same models, the highest output figures differed by the gap 7 °C.

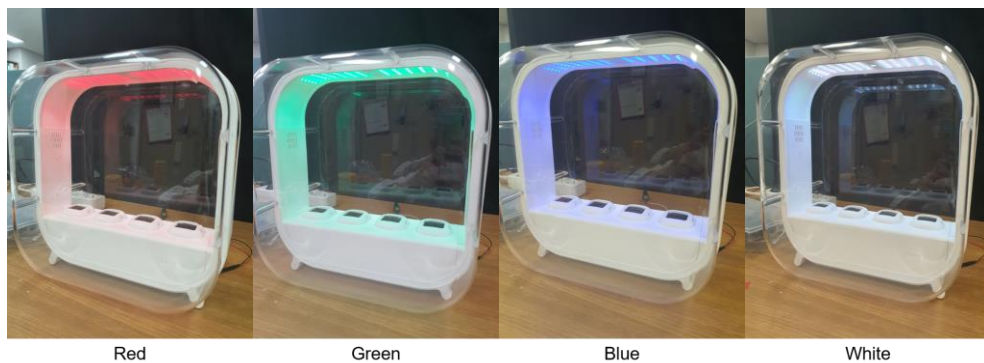


**Fig. 33 Heater1 and Heater2 in operation together with the numbers of duty cycle.**

#### 3.2.2.4. LED

Three light regimes were developed and changed to white light if the three lights were turned on at once. Because they were controlled by duty cycles, it showed different brightness upon signals. Different light quality and intensity became controllable with this system.

In this study, the ratio of three lights was not adjusted by the number of diodes, but by intensity of each light. That is, both dimming and brightening could be implemented.

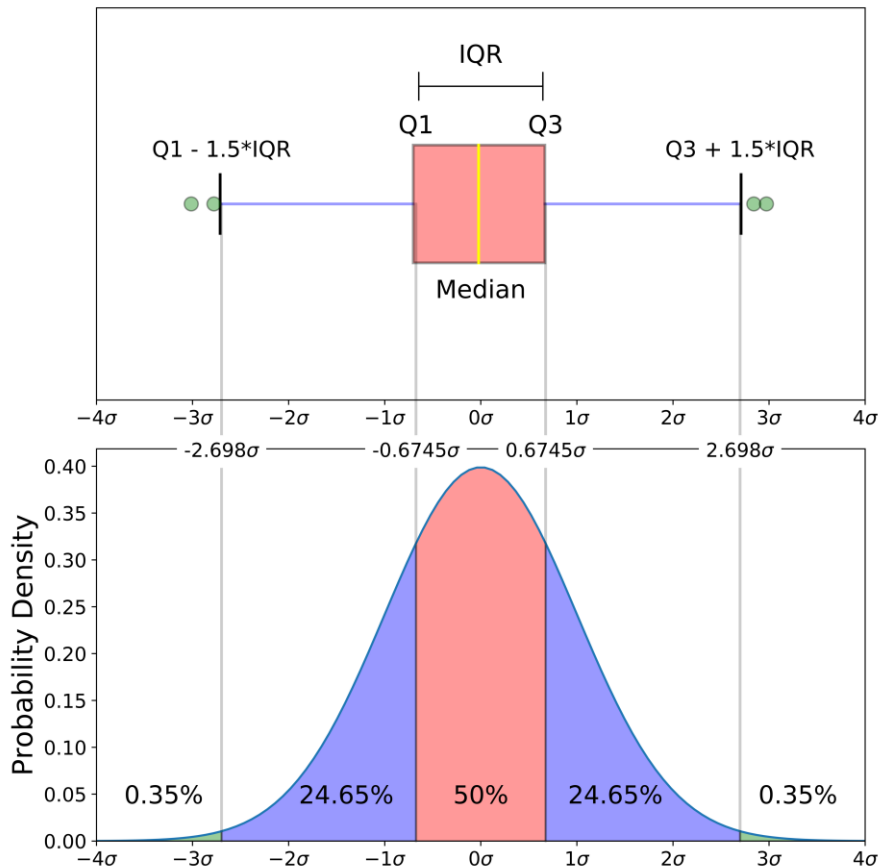


**Fig. 34 LED in operation changing light quality together with the numbers of duty cycle and signals.**

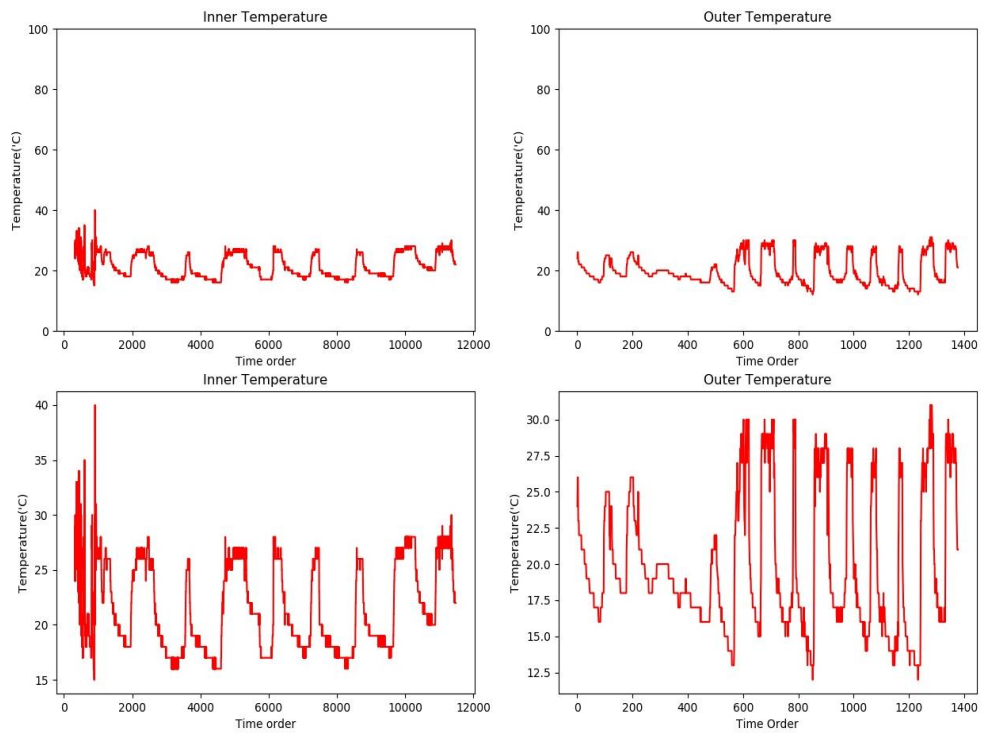
### 3.2.3. Results of Integrated system

#### 3.2.3.1. Unprocessed data of temperature and humidity

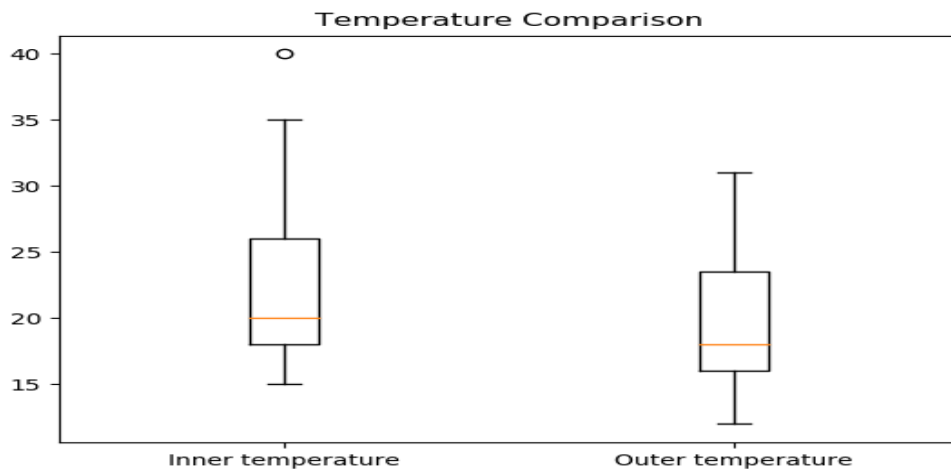
The unprocessed data showed the trends of inner and outer temperature and humidity as shown in Figs. 36 and 38. In the box plots in Figs. 37 and 39, there were some outliers in temperature and significantly many outliers were marked in humidity. For accurate analysis, all outliers were to analyze accumulated data.



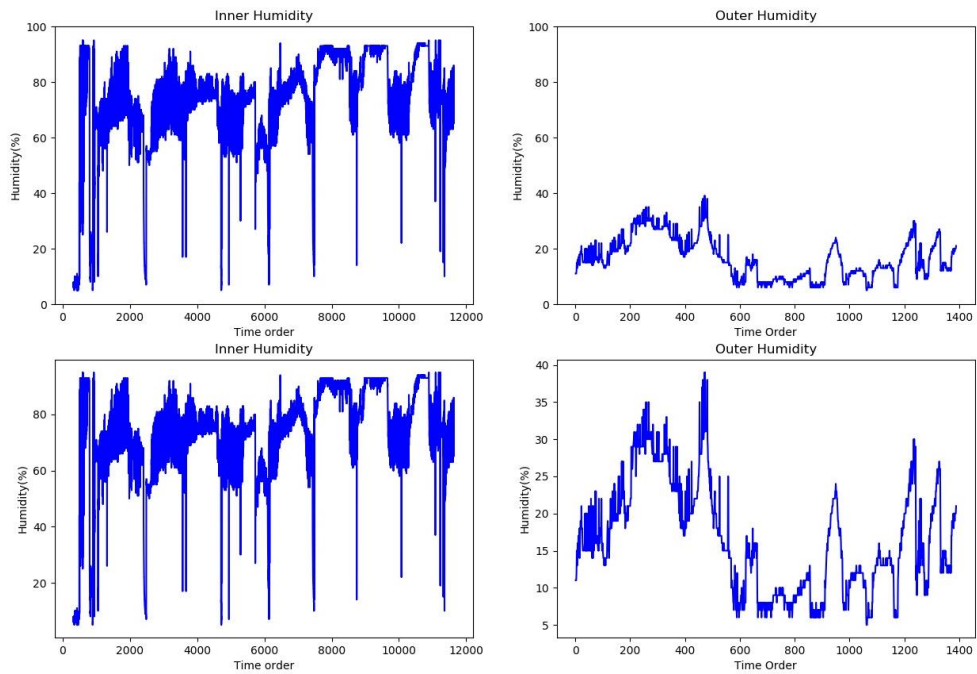
**Fig. 35 Concept of Boxplots (Understanding Boxplots. The image above is a boxplot. A boxplot... | by Michael Galarnyk | Towards Data Science n.d.).**



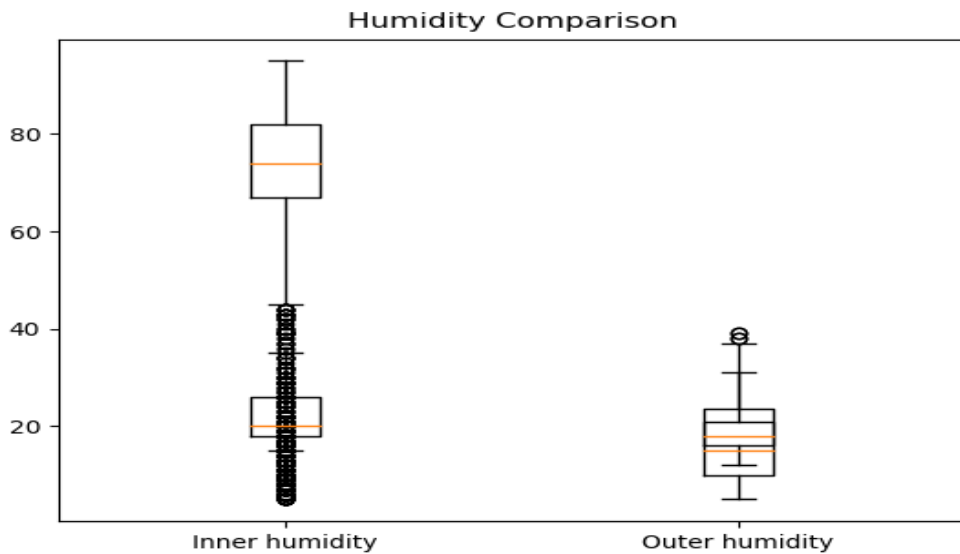
**Fig. 36 Trends in inner and outer temperature based on unprocessed data including outliers.**



**Fig. 37 Box plots for comparison between inner and outer temperature based on unprocessed data including outliers.**



**Fig. 38 Trends in inner and outer humidity based on unprocessed data including outliers.**



**Fig. 39 Box plots for comparison between inner and outer humidity based on unprocessed data including outliers.**

### 3.2.3.2. Outliers removal

#### 3.2.3.2.1. Statistics

To eliminate the detected outliers, IQR (Inter Quantile Range) method was used. The result of the statistics from the processed data was presented in Table 3.

**Table 3. Statistical results of temperature and humidity.**

	<b>Inner temperature</b>	<b>Inner humidity</b>	<b>Outer temperature</b>	<b>Outer humidity</b>
<b>mean</b>	21.24016	75.58338	19.80717	16.57348
<b>std</b>	3.705304	10.27804	4.701043	7.304271
<b>min</b>	16	49	12	5
<b>25%</b>	18	69	16	10
<b>50%</b>	20	75	18	15
<b>75%</b>	25	82	23	22
<b>max</b>	31	95	31	39

In the control system, the temperature was maintained between 16 °C and 31 °C, with an average of 21.2 °C, whereas the external temperature of the system was in the range from 12 °C to 31 °C with mean value of 19.80 °C. Basil must be grown in the temperature from 21 °C to 26 °C, and not below 18 °C.

Herein, basil will be able to survive more than 75 % with the control system because values of the first and third quartile were 18 °C and 25 °C each.

However, without the control system, basil cannot survive, less than 75 % as values of the first, second and third quartile were 16 °C, 18 °C, and 23 °C each.

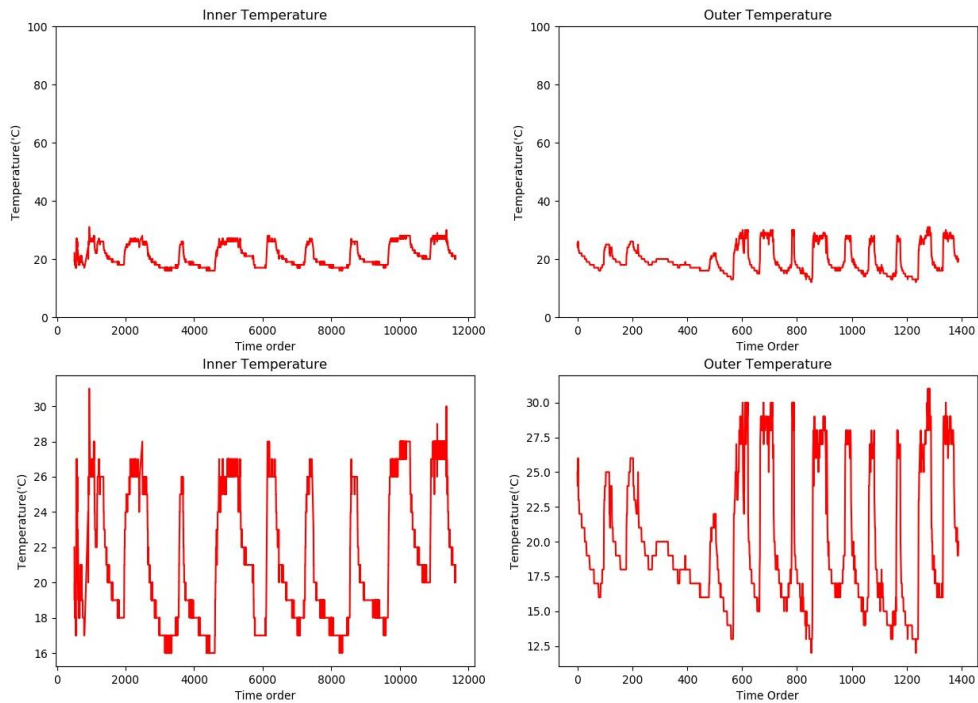
From studies, basil withers rapidly in dry airflow. Hence, it requires significant humidity over 60 % compared to other plants do, more than 45 %.

Herein, basil under this control system can grow significantly because the mean values of the inner and outer humidity were 75.58 % and 16.57 % respectively. Because dry airflow perishes basil very rapidly, basil under the outer temperature that was not managed by the fuzzy logic control system cannot survive because even the maximum value of humidity was observed as 39 %. However, the ideal humidity for basil is between 60 % and 65 %, except for the germination period that requires from 80 % to 90 %. Under high humidity, it can become weak and infected as other plants do. So, fuzzy control system performed efficiently to maintain high humidity, although significantly complex control was required to maintain the temperature in the ideal range.

There can be several methods to achieve controlling temperature and humidity. One can be setting rules precisely. Another can be changing the input variables to suitable values (sensed inner temperature or humidity – setting temperature or humidity). Other methods can include locating devices to maximize respective functions.

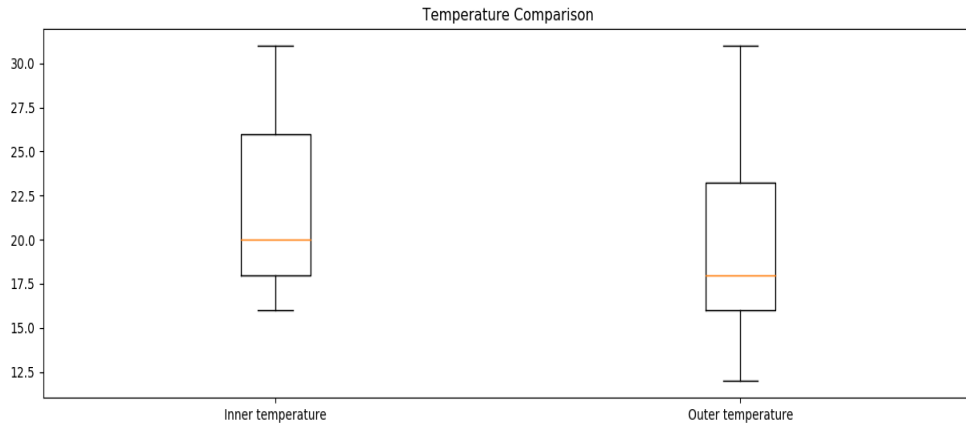
### 3.2.3.2.2. Data Visualization

Together with the statistics, the graph in Fig. 40 showed the trends of temperature with no outliers. The outer temperature had wider variations compared to the inner temperature. Although the inner temperature was recorded every minute, whereas the outer temperature was recorded every fifteen minutes, the total peaks was high in the outer temperature. Therefore, the environment under the control system is significantly stable.



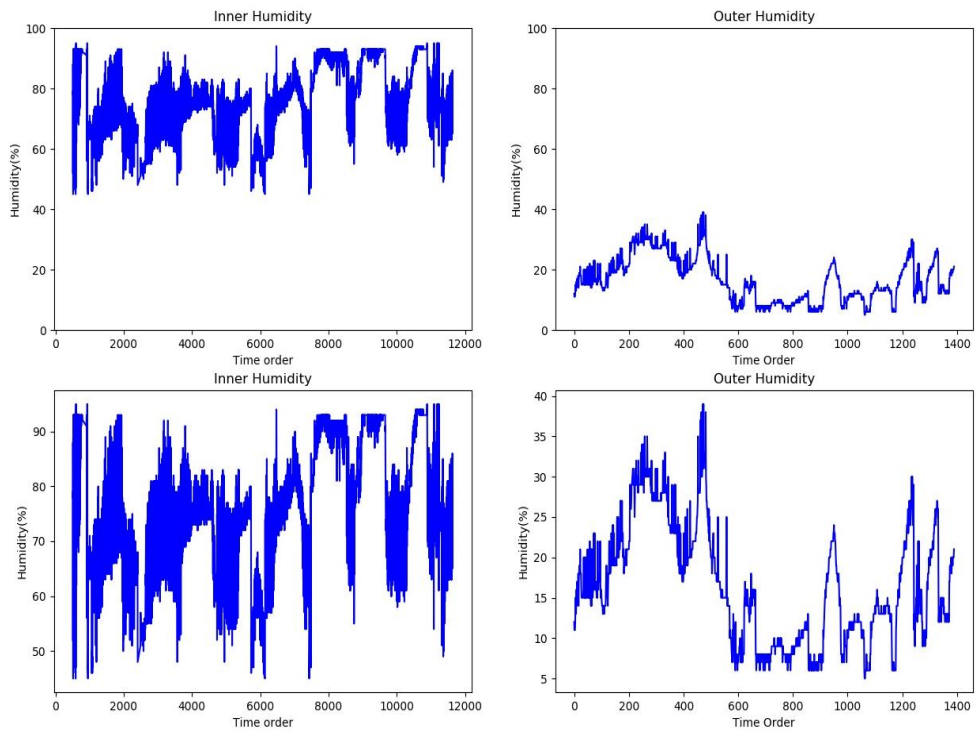
**Fig. 40 Trends in inner and outer temperature based on processed data excluding outliers.**

*The difference between upper and lower graphs is the range of temperature.*



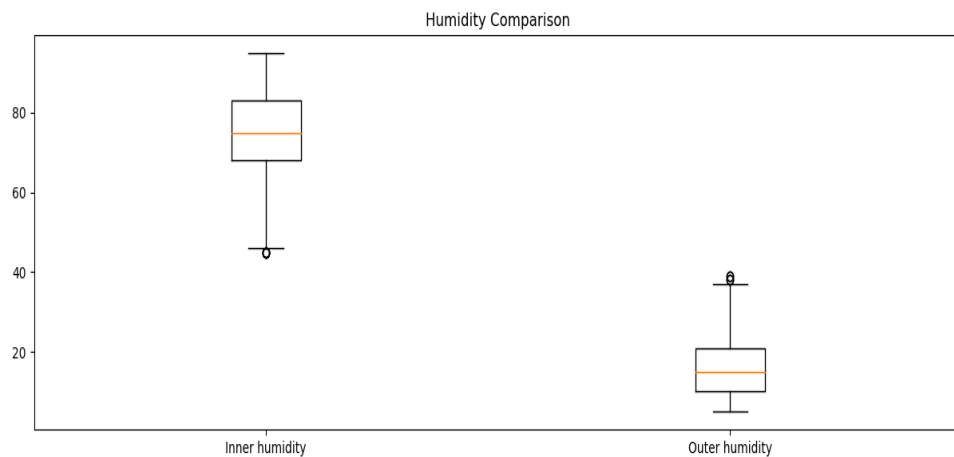
**Fig. 41 Box plots for comparison between inner and outer temperature based on processed data excluding outliers.**

Together with the statistics, the graph in Fig. 42 showed trends of humidity with no outliers. Outer humidity has significantly low values compared to that of inner humidity, indicating significantly dry air condition. Outer humidity could be affected by human's activity because it represents indoor air conditions, that means the changes in environment is unpredictable. The values of the outer humidity showed precisely the problem whereas the inner humidity showed some pattern. The pattern in the inner humidity data showed the mist generator was operating efficiently; if humidity reduced, the mist generator operated to reduce the effect. Nevertheless, it remained high in humidity than intended and must be reduced.



**Fig. 42 Trends in inner and outer humidity based on processed data excluding outliers.**

*The difference between upper and lower graphs is the range of humidity.*



**Fig. 43 Box plots for comparison between inner and outer humidity based on processed data excluding outliers.**

### **3.2.3.3. LED Changes**

From the 5<sup>th</sup> day to 10<sup>th</sup> day, the three LED lights were all automatically changed based on the membership functions of growth stage (duration) and three output variables (red, blue, green). Duty cycles of red and green were increased from 22.59 % to 60 % and those of blue were increased from 60 % to 87.36 % whereas the growth stage changes from germination to vegetative growth. (Table 4)

Also, as the vegetative period rose to the 40<sup>th</sup> day whereas its fuzzy membership functions reduced and flowering period began and its fuzzy membership functions rose from the 35<sup>th</sup> to 40<sup>th</sup>. From the 40<sup>th</sup> day, the final values were constantly kept until the last day. Along these changes, the three light values were continuously changed. Duty cycles of red and green rose from 60 % to 87.36 % and those of blue descended from 87.36 % to 22.59 %.

Some study proposed that raising seedlings treated with blue light promoted the growth of lettuce whereas generally maintaining dark in germination (Johkan et al. 2010). In this study, lighting with weak red and green and a considerably stronger blue, was shed on basil seeds.

However, it would be appropriate to grow basil if the values of blue show higher in the vegetative growth up to 100 % by changing membership functions of Blue because blue light had a positive impact on sweet basil (Aldarkazali et al. 2019a).

Otherwise, red and green were appropriate. They were lower than blue

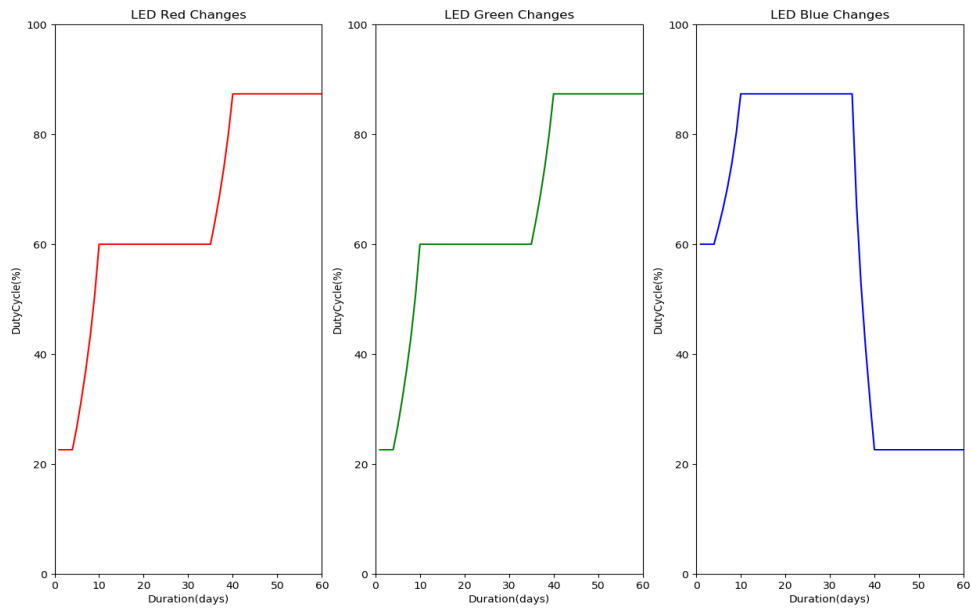
with the ratio of 2.66 when seedling and 1.46 in the stage of vegetative growth. Also, they were higher than blue with the ratio of 3.87 when flowering.

There were considerable materials to be considered in setting the three light regimes. Among them, there are two conflicting results in the ratio of lighting with three lights.

Green light interferes basil's growth and development and BR LED regime doubling the blue to the red had a significant positive impact on the quantity and quality of essential oil extracted from sweet basil, that might alter the taste of basil. (Aldarkazali et al. 2019b)

Furthermore, basil under blue, green and red light (ratio 1:1:1) has no difference in phenotype compared to that under BR light (ratio 1:1). In addition, BR light (ratio 1:1) does not result in the expected horticulturally optimal basil growth if compared to any combination of three wavelengths (S. D. Carvalho et al. 2016).

In this study, green light was not excluded and blue was expected to remain in higher position except for flowering stage dominated by red and green light.



**Fig. 44 Red, Green, and Blue of LEDs changes upon days of duration**

(a) Respective result of red, green, and blue LEDs upon duty cycle.

(b) Comparison of changes in the three lights of LEDs.

**Table 4. LED Changes**

Duration	Red	Green	Blue
1	22.59259	22.59259	60
5	26.74993	26.74993	63.07749
6	31.66375	31.66375	66.43025
7	37.0625	37.0625	70.22628
8	43.21631	43.21631	74.69834
9	50.63662	50.63662	80.25072
10	60	60	87.35868
36	64.16863	64.16863	66.95827
37	68.75202	68.75202	52.62398
38	73.94265	73.94265	41.31238
39	80.00999	80.00999	31.57476
40	87.35868	87.35868	22.59259

### **3.2.4. Correlation between Input and Output variables**

#### **3.2.4.1. Group1 (Temperature, Humidity)**

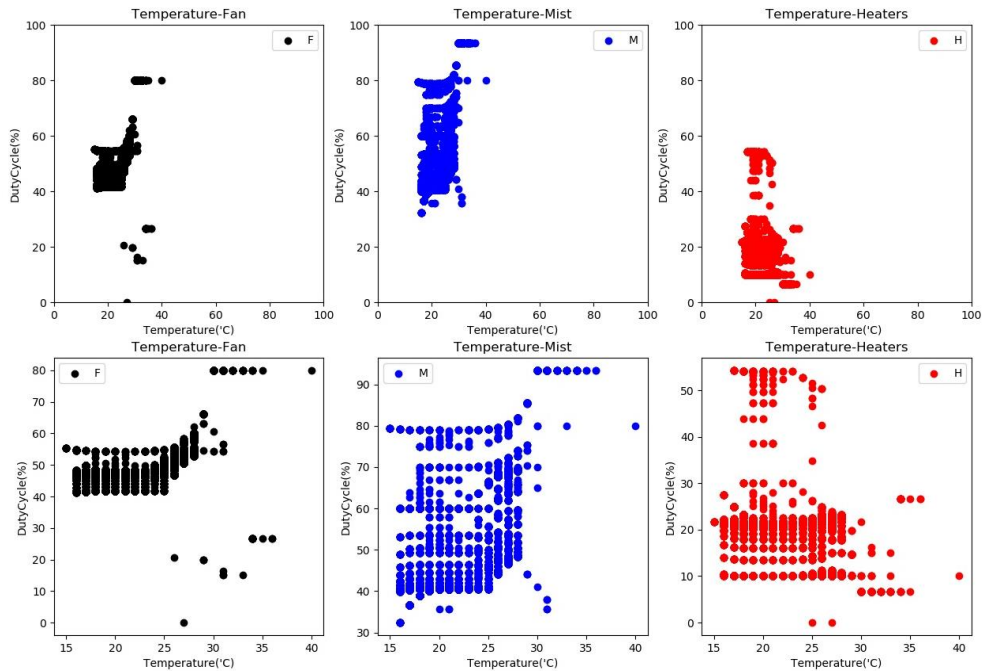
Under the hypothesis that input variables of humidity and temperature and output variables of fan, mist and heaters could have associations with each other, scatter plots were drawn with those variables to investigate these relations.

Increasing the temperature reduced the fan and heaters operations and increased the mist operations. However, the inclinations of fan and heaters were not clear, because there were fan's and mist's dots on the upper and lower sides in some ranges of temperature; high temperature over 30 °C, and medium temperature under 30 °C respectively (Fig. 45). They did not operate accurately in maintaining associated rules. It was expected to show distinct flows; fan of (Average – Slow – Fast), mist of (Weak – Medium – Strong), and heaters of (High – Average – Low) as temperature increased.

For humidity, the tendencies significantly appeared. If humidity was lower than 40 %, fan maintained high output and it began decreasing in operation until reaching 50 %. Then, it remained on the level up to 70 %, and thereafter rose. In case of mist and heaters, they reacted negatively and positively each. That is, if humidity increased, mist reduced continuously and heaters increased. These inclinations showed the intentions of rules 1, 2, and 3 (Fig. 46).

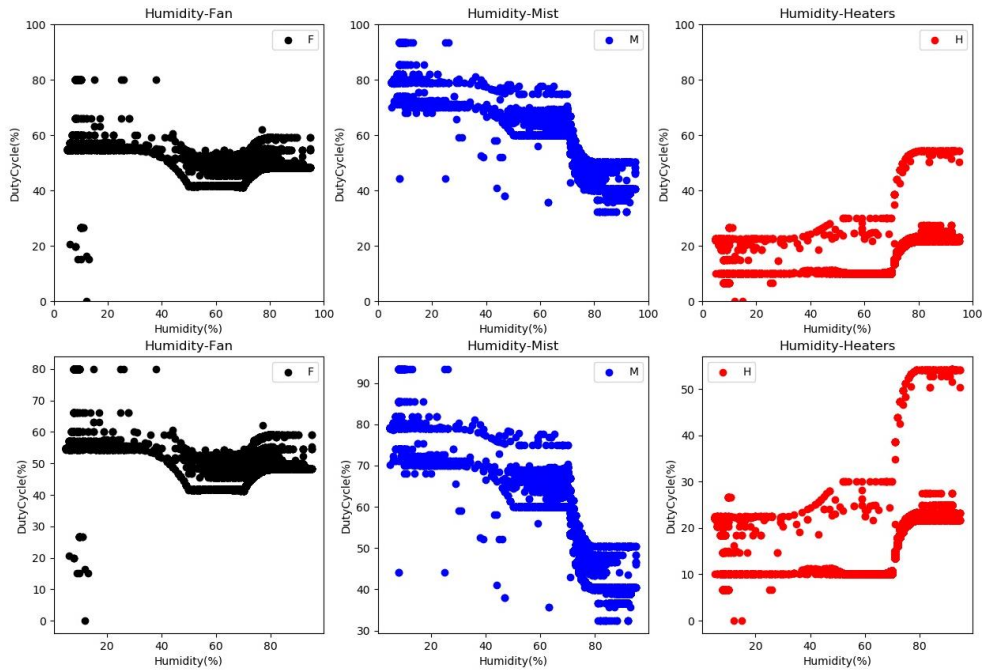
It was dubious of the accuracy of temperature's interrelated membership functions (fan, mist, heaters) because they were not consistent with the rules.

If not, it is surmised that the rules were inconsistent with humidity related ones. Herein, the rules of temperature and humidity should have been separated and partitioned. However, the former proposition was reasonable because humidity's associated flows expressed tendencies, particularly in temperature's membership functions.



**Fig. 45 Relations between temperature and three output variables; fan, mist, and heaters (heater1 and heater2).**

*Upper graphs are magnified into lower graphs.*



**Fig. 46 Relations between humidity and three output variables; fan, mist, and heaters (heater1 and heater2).**

*Upper graphs are magnified into lower graphs.*

To particularly define correlations between the two input variables (Temperature, Humidity) and four output variables (fan, mist, heater1, heater2), Pearson's correlation coefficients were adopted.

Pearson's correlation coefficient is the test statistics measuring the statistical relationship between two continuous variables based on the method of covariance. The coefficient values ranges from +1 to -1, where +1 indicates a complete positive relationship, -1 indicates a complete negative relationship, and zero indicates no relationship exists.

From Fig. 47, the strongest correlation was formed between mist and humidity with a value of -0.84. It implies the strong negative relation

between the two components. In particular, the mist generator operated strongly if humidity reduced.

Furthermore, mist had a strong positive relation with temperature and negative relation with heaters (heater1 and heater2) with values of 0.67 and -0.55 respectively. If the temperature increased, the mist operated to reduce it. Because both mist and heaters were output variables, it could be interpreted that heaters were on and mist were off if the system was heated.

In addition, temperature had strong relations with humidity and fan having values of -0.52 and 0.52 each. At lower temperature, humidity remained high. If the temperature fell, fan worked less. To explain this aspect, all components must be combined and considered together. If temperature increased, fan and mist performed significantly and heaters performed less to cool it.

Temperature had a medium negative correlations with heaters, with a value of -0.38. Moreover, (humidity–heaters, 0.49), (mist–fan, 0.37) and (humidity–fan, -0.38) were also medium correlations. If temperature increased, heaters considerably reduced its operations. Because the mist and fan were output variables, it was defined as coupled. If mist was on, fan was on. If humidity increased, heaters operated more and fan activated less at medium level.

Lastly, fan and heaters were identified with no correlation because its correlation coefficient was 0.01, nearly a zero.

The following problems were identified from the values of the

coefficients.

First, fan should have been related to mist and heaters similarly and strongly because it significantly enhanced the effect of controlling temperature and humidity with mist and heaters other than ventilation.

However, the Pearson's correlation coefficients indicated that the original intention for fan was not achieved because the values with mist and heaters were 0.37 and 0.01 respectively. It showed that the system entirely missed the correlation between heaters and fan. Although mist and fan had a positive correlation, it was still weak. Both numbers should have been at least over 0.5.

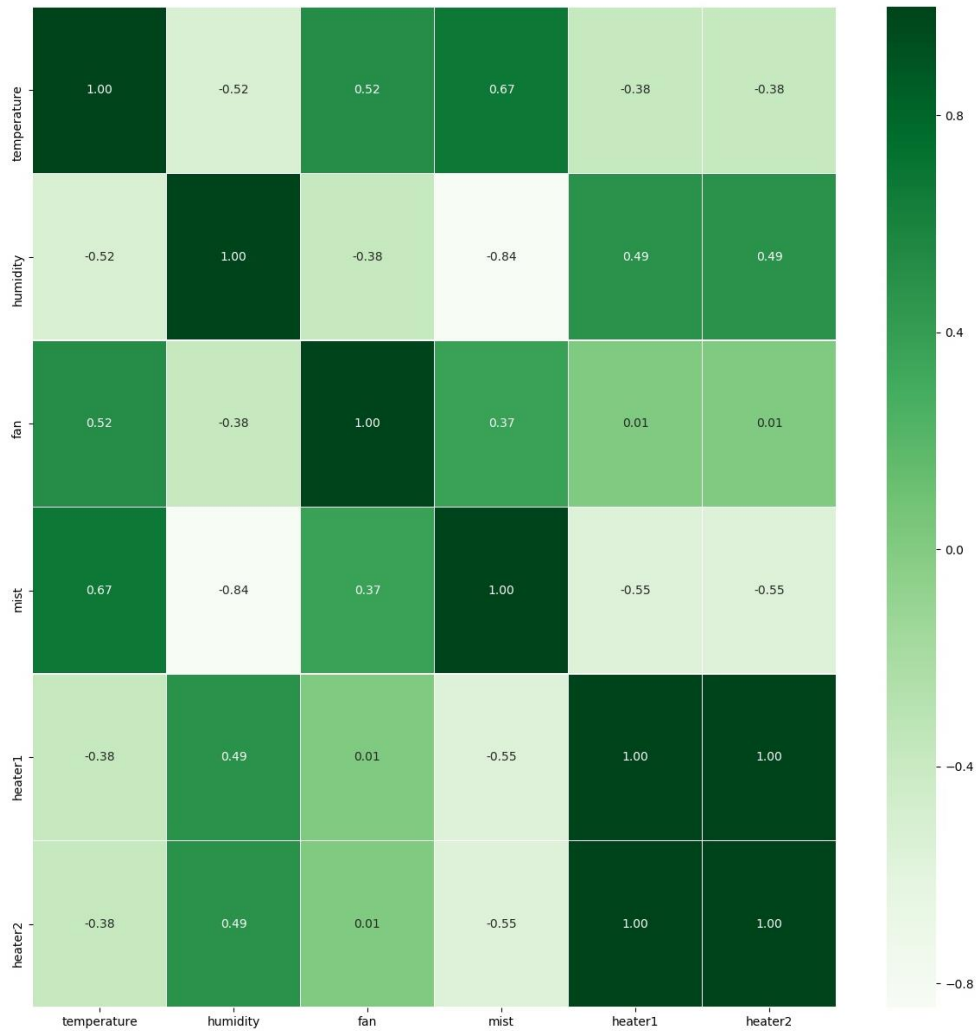
To address these problems, rules and membership functions of fan, mist and heaters should be redesigned and applied. Then, humidity and temperature will be controlled as desired.

Second, humidity and fan had lower correlations than expected. It is assumed that this was why humidity was maintained higher than 65%. It must be fixed by modifying related rules and membership functions of humidity and fan.

Finally, the correlation between temperature and heaters was way weaker than hypothesized. Heaters and mist had direct connection to controlling temperature. Therefore, they must show strong correlations with temperature. However, heaters presented medium correlations of -0.38 with temperature whereas mist had a strong correlation of 0.57. The proposed value was over the absolute value of 0.8 for both similar to the association

between humidity and mist, -0.84. Consequently, the temperature would be adjusted more efficiently.

In case of three lights, correlations were not estimated since the intention was that each light should be operated independently upon days of duration.



**Fig. 47 Heatmap describing correlations between two input variables (temperature, humidity) and four output variables (fan, mist, heater1, heater2) based on Pearson's correlation coefficients.**

#### **3.2.4.2. Comparison between results of simulation and actual operation**

To compare results of actual operation to those of simulation, cross sections of surface view in simulation were attained. This was because output variables such as fan, mist and heaters were affected by temperature and humidity at the same time during actual operation. In other words, cross sections had to be gained in three-dimensional surface views to consider the other parameter together simultaneously.

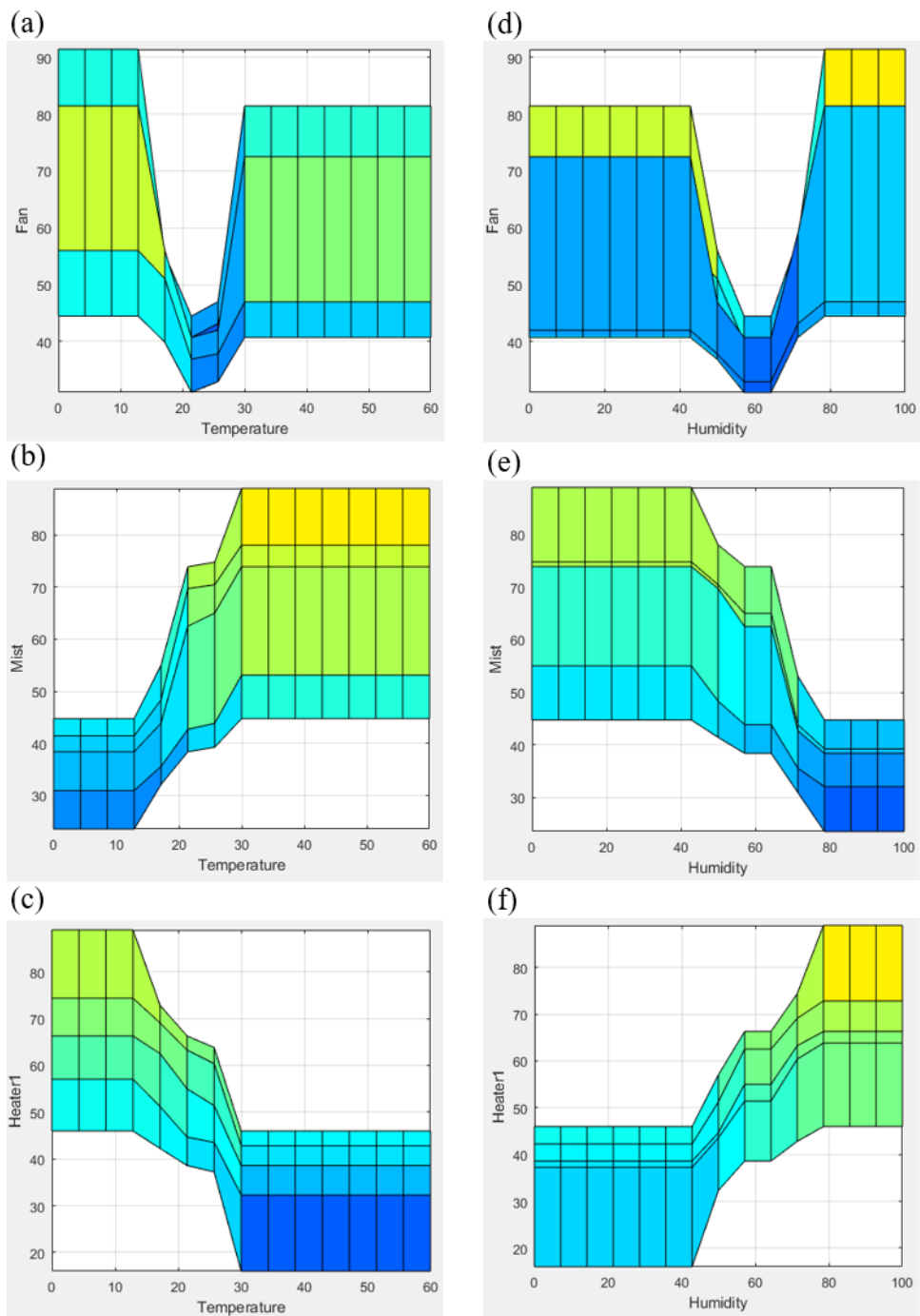
The areas of cross sections in surface view of simulation had been lapped over the graphs of results from actual operation to see how differently it operated with simulation.

When analyzing data from actual operation only, as mentioned earlier, tendencies were clearly observed in correlations related to humidity while those related to temperature were ambiguous. In terms of associations in temperature, fan's was hardest to be analyzed since any trend was hardly noticed. And the other two, mist's and heaters', slightly showed inclination; positively in mist's and negatively in heaters'.

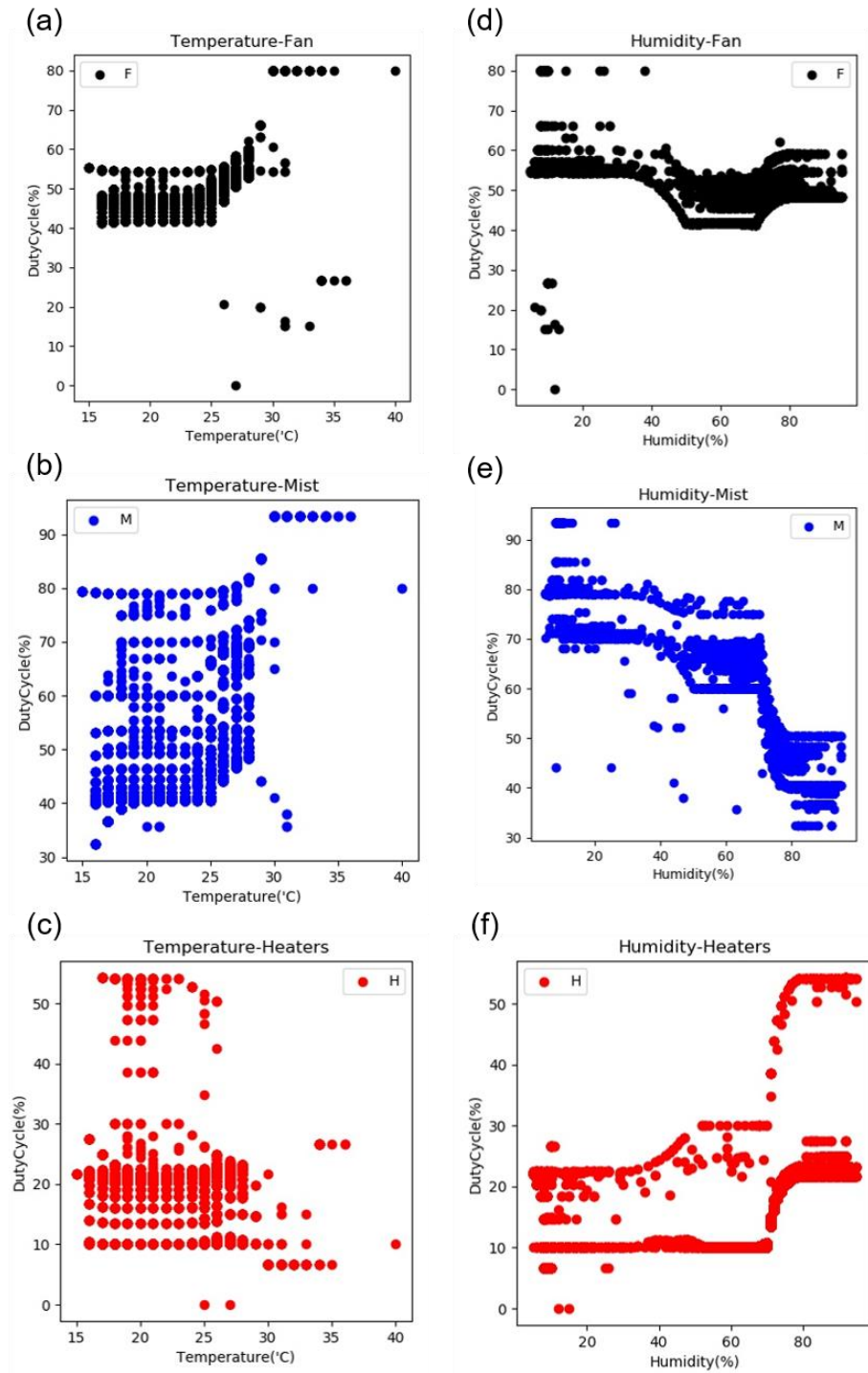
However, after overlapping results of simulation on those of actual operation, other interpretation could be drawn. Fan and mist in both temperature and humidity mostly activated within the areas of simulation. However, heaters' work largely broke the bounds of simulation even though trends, going up as humidity went up and going down as temperature went down, were kept. It means, heaters actually worked inappropriately.

Especially, heaters' duty cycles should have been much higher below 30 °C of temperature and over 45% of humidity. Given that the mean value of inner temperature in statistical results (Table 3) was 21.24016, it could have been higher. As the max value of inner temperature was already 31 which is out of ideal range, this inappropriate working range might have been more fit to this system than previously designed.

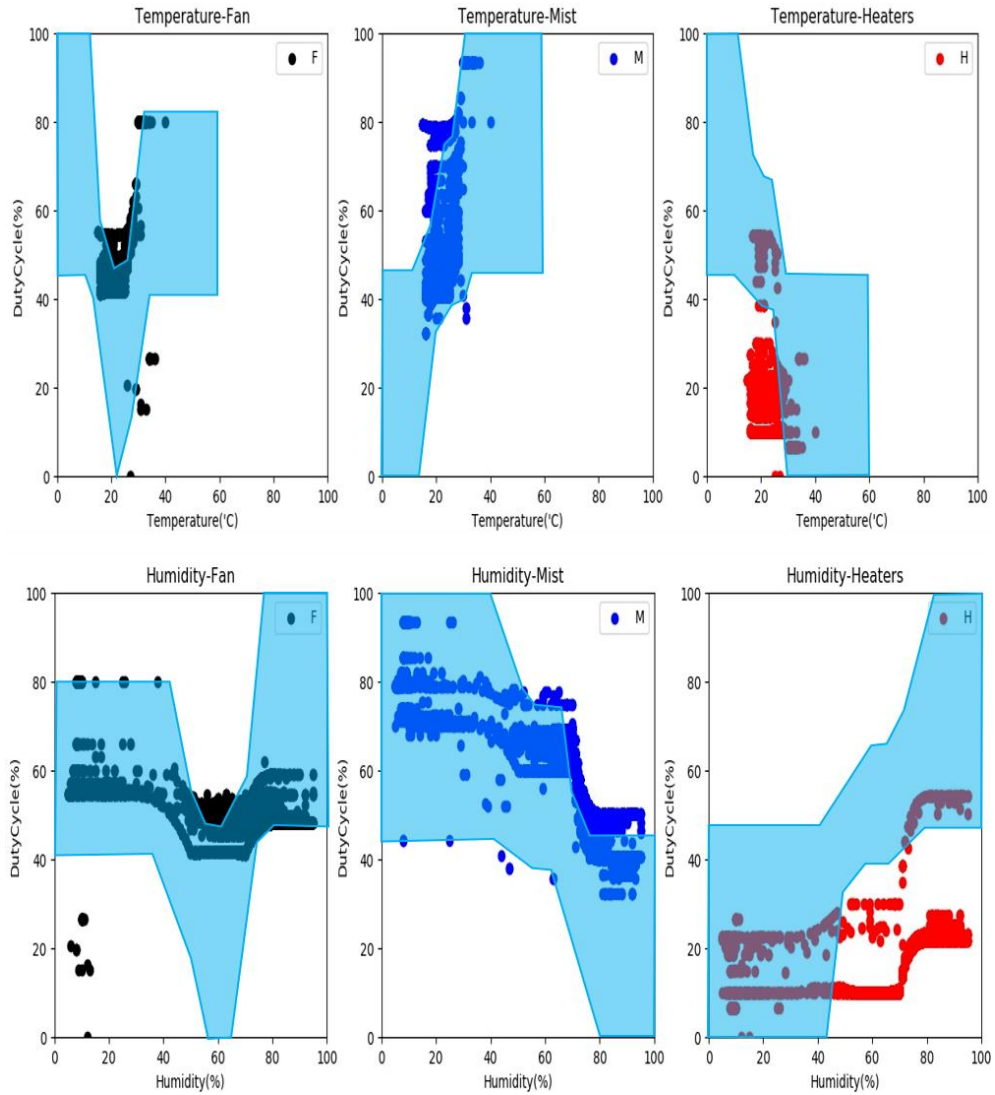
In case of LEDs, there were small differences between simulation and actual operation. When it was 36<sup>th</sup> day, results of simulation were (64.3, 64.3, 67.1) and those of actual operation were (64.2, 64.2, 67) on red, green, and blue each. On the day of 7<sup>th</sup>, (35, 35, 68.9) in simulation and (37.1, 37.1, 70.2) in operation were drawn. On 27<sup>th</sup> day, (60, 60, 87.6) in simulation and (60, 60, 87.4) were collected. (Fig. 29, Table 4) That's why LEDs had been implemented appropriately.



**Fig. 48 Correlations in Simulation**



**Fig. 49 Correlations in Actual Operation**



**Fig. 50** Overlap area of Simulation and Actual Operation.

## **Chapter 4. Conclusions**

The three objectives of this study are as follows.

To control three lights in the growth stages of plants under the fuzzy logic to automatically adjust light quality and intensity affecting crop quality.

To apply Pearson's correlation coefficient as a method to examine the fuzzy logic and compare results from simulation with those from actual operation as a method to detect weakness in actual operating system.

To examine the factors to consider if developing household harvesting hardware.

Consequently, the system controlled three lights based on defuzzified values from fuzzy logic in the plant growth stages (in days) indicating the growth stages on automatic pilot. It was observed that light quality and intensity could be automatically controlled by fuzzy logic.

Also, temperature and humidity were logged as more than 75 % remained in the range of 19 – 26 °C with an average of 21 °C for temperature that are favorable environment conditions for basil.

Although temperature was well-managed and humidity was high, humidity reduced to set ranges from 60 % to 65 %. That is, more than 10% should be reduced.

To adjust the fuzzy logic, each variables' correlation was investigated considering the characteristic that fuzzy logic's variables depend on each

other. In this context, Pearson's correlation coefficient was selected to examine rules and membership functions that are significant to FLC.

It was assumed that fan was the main defect of this system. Its correlations were small to most of related variables; 0.37 with mist, -0.38 with humidity, 0.01 with heaters. In contrast, mist developed significantly strong correlations with other variables; 0.67 with temperature, -0.84 with humidity, -0.55 with heaters.

Fan was a core component of this system because it was responsible for ventilation, controlling temperature and humidity simultaneously. Consequently, it developed significant association with every other variables.

However, this important concept was not recorded in the control system, hence the system losing its precise performance.

In addition, heaters activated improperly when comparing to simulation. Nonetheless, the statistical results of temperature showed appropriate range for cultivating sweet basil. Therefore, heaters' membership functions and rules should be changed on the basis of results from actual operation.

Consequently, this system can perform accurately If the rules and membership functions related to fan and heaters are modified.

In developing the FLC system, there were several factors relating to hardware structure to consider in.

First, the cultivator's material affects thermal conductivity. The cultivator used for this study was developed from ABS. Although two heaters were set

up on both sides of the pillars, the uniformity and efficiency of heat conductivity was not observed.

Second, water tank for generating mist should be positioned away from the heaters. Mist can raise humidity and reduce the temperature. If the water tank is close to the heaters, the water's temperature increases and its function of decreasing temperature reduces.

Third, fan motors for ventilation must be distant from heaters and mist generators. That is, it should not be tilted to one side between heaters and mist generators in a position. From this study, an ideal system can be expected to have four fan motors; two for ventilation (one for intake and exhaust each), one for heating and one for nebulization.

Fourth, the sensor sensing humidity and temperature should not be affected by any device. Because the value of the sensor significantly affects the system, it should be positioned in a neutral position from the heaters, nebulizer, and fans.

Finally, for precise control, the system should be closed completely. Because the cultivator of this study was closed with six tiny magnets, the humidity reduced immediately right after the mist generator stopped. That shows why mist was controlled based on duty cycle, and also the reason of changing water tank from the three-dimensionally optimized printing tank to the larger tank, the bear-shaped tank. Consequently, the water tank was filled daily causing fluctuation in the environment. Therefore, filling the water tank should be easy for use, and must not affect the environment. That

is, the water must be positioned outside the sealed space, sufficiently large for constant humidifying although easy to refill. If the space is enclosed perfectly so that humidity can be maintained, the reducing rate of water would be lower. This implies that large water tank or frequent water replacement are not required. Furthermore, it will lead to yield a reduced operating time.

The two contributions of this study are as follows.

Lighting is adjusted optimally based on growth levels by controlling red, green, and blue light separately. This increases the ability of controlling light quality leading to enhance crop quality and additional economic value.

Home gardening market can grow significantly with this product. The number of family members is decreasing and the amount of necessary foods gradually becomes low. In this trend, many products targeting a family have been introduced. The product in this study will be fit to this flow. However, only home gardening market does not follow this trend. It is in contrast as with Samsung and LG electronics developing a cultivator as large as refrigerator for the public. Beginners of home gardening can obtain high quality of crops with this system.

As a further study, it is assumed that managing plants with this system will be easier and efficient if a camera is used to measure and calculate plants' growth levels. By the method of object recognition using a RGB camera based on deep learning, it will be accurate and can consider several species simultaneously.

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# 스위트 바질 재배를 위한 생육 단계별 가정용 퍼지 로직 기반 제어 수경재배 시스템 개발 연구

김 정 선

## 국문 초록

토양에서 대기까지의 범위가 넓어지면서 환경 오염이 심화됨에 따라 실내 농업에 대한 수요가 증가하고 관련 연구도 증가하고 있다. 실외 기후 조건에 영향을 받지 않는 안정적인 실내 재배 시스템과 공간을 최대한으로 활용하는 효율적인 시스템에 대한 연구가 지속적으로 가속화되고 있다. 대부분의 연구는 산업 농업 또는 대규모 생산에 중점을 두는 경향이 있으나 가정을 위한 소규모 재배도 많이 개발되어야 한다. 이 연구는 Raspberry pi 4 및 Python을 사용하여 퍼지 논리에 의해 자동으로 제어되는 가정용 수경 재배 시스템을 만들기 위해 설계되었다. 애매한 상황을 해결하고 챔버 내부의 환경 제어를 개선하기 위해 퍼지 로직 제어 (FLC)를 채택했다. FLC의 경우 3 개의 입력 변수와 7 개의 출력 변수가 사용되었다. 입력 변수는 온도, 습도 및 성장 단계 (기간)이고 출력 변수는 팬, 미스트, 히터 1, 히터 2, 그리고 3 개 (적색, 녹색, 청색) LED이며, 6 개의 FLC 퍼지 규칙이 적용되었다. 이 FLC는 각 성장 단계마다 다른 휘발성 화합물과 식물의 맛을 유발하는 다양한 광질과 밀도가 필요하여 세 가지 조명이 각각 세 단계의 재배 기간 동안 작동되도록 설계되었다. 그 결과 제어 시스템 내부 온도는 외부 온도 19.8 °C에 비해 21 - 26 °C (평균 21.24 °C)로 유지되었으며, 내부 습도의 평균값은

외부 습도 16.57 %에 비해 75.58 %로 유지되어 시스템을 통해 바질 재배에 적합한 환경이 조성되었다는 것이 확인되었다. 그러나, 습도가 60 - 65 % 수준으로 낮게 유지되면 더욱 적합한 환경이 조성되므로 이 문제를 해결하기 위해 Pearson의 상관 계수를 사용하여 규칙과 멤버십 함수를 분석했다. 팬과 히터, 습도, 미스트와의 상관 관계가 예상보다 낮았기 때문에 문제의 주요 원인은 팬과 관련된 것으로 추정된다. 게다가, 시뮬레이션과 실제 작동 사이의 비교가 수행되었으며 히터의 실제 작동이 시뮬레이션의 영역을 벗어나 부적절하게 이루어졌다는 것을 발견했다. 마지막으로, 광질은 지속 시간에 따른 세 가지 빛 파장 영역 (발아 및 잎의 성장을 위한 청색광, 개화를 위한 적색광, 잎의 캐노피를 통한 생육 저하를 방지하는 녹색광)을 기반으로 FLC에 의해 잘 제어되었다. 추후 RGB 카메라를 사용하는 머신 비전으로 성장 단계를 추정하면 조명 제어가 더 정확해질 것으로 기대된다.

**주요어 :** 가정용, 수경재배 시스템, 스위트 바질, 퍼지 논리 제어, 생육 단계, LED 광

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