DESIGN OF AN AUTOMATED RAINWATER HARVESTING SYSTEM FOR URBAN AGRICULTURE

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A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Honours) Chemical Engineering

Lee Kong Chian Faculty of Engineering and Science
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September 2022

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DESIGN OF AN AUTOMATED RAINWATER HARVESTING SYSTEM FOR URBAN AGRICULTURE"** was prepared by **LOH YIK WEI** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Chemical Engineering at Universiti Tunku Abdul Rahman.

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Date : 22 September 2022

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ABSTRACT

Rainwater harvesting system (RWHS) is gaining attention as an alternative water source for agriculture worldwide as agricultural sector utilities approximately 70% of freshwater supply and is projected to increase by 20% from 2014 to 2040. This study is based in Klang Valley, Malaysia where water crises have been rampant throughout the years due to water pollution and flash floods. This has affected the freshwater supply in the country, led to a demand for RWHS. The average cost of installing a RWHS typically costs between RM 1,500 to RM 10,000 depending on their specifications and functionality. Although rainwater is a potential source for non-portable use, harvested rainwater for urban agriculture may require better quality monitoring and control. Without proper quality control, pollution in harvested rainwater may be a threat to crops, soil and human health in urban agriculture. Therefore, this project aims to propose a minimal viable design of an automated RWHS to support sustainable urban agriculture by reducing freshwater consumption and integrating quality control automation. The proposed system is equipped with a pH sensor, and a float sensor to monitor the water quality and level of rainwater harvested. Electrical conductivity was also tested physically in order to determine the water quality of rainwater harvested. The prototype proved that it is viable for urban agriculture use as with the aid of an automation system, it could harvest rainwater that meets the irrigation standard and also discharge unqualified rainwater. A comparative study of two different automated designs, first design - with a first flush diverter versus and second design - with a fine mesh filter were examined, and the results indicated that the fine mesh filter design showed greater potential in water and cost conservation as it could harvest a greater volume of rainwater. The total cost of the system with a first flush diverter in five years of operation is RM 6,634.45 whereas the system with a fine mesh filter is RM 6,634.45 and the payback period was 2.97 years and 3.37 years, respectively. Therefore, an automated RWHS with a first flush diverter was chosen as the viable design for urban agriculture as it could preserve better water quality of harvested rainwater and reduce the maintenance cost in the long run.

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cm	centimetres
h	hour
in	inch
in^2	square inches
km^3	cubic kilometres
kWh	kilowatt-hour
kWh/y	kilowatt-hour per year
L	Litres
L/d	Litres per day
L/h	Litres per hour
L/y	Litres per year
m	meters
m^2	square meters
m^3	cubic meters
mg/L	milligrams per litre
min	minutes
mm	millimetres
pc	piece
pcs	pieces
V	voltage

IoT	Internet of Things
MCO	Movement Control Order
RM	Ringgit Malaysia
RWHS	Rainwater Harvesting System
WHO	World Health Organisation

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

During the Roman Empire, rainwater harvesting became a form of art and science, and many cities also adopted the technology. In the past, the Romans were experts in technological discoveries, and made significant improvements during Emperor Caesar's reign. One of the most magnificent rainwater harvesting structures is located at the Sunken Palace, in Istanbul (Ezekiel Rochat, 2018). It was used to harvest rainwater from the rooftops, and it was so huge that a boat could sail around in the area. Besides, in the 17th century, an island of Maltra constructed an aqueduct to harvest rainwater to meet the water supply demands as the population increased (Ezekiel Rochat, 2018). Rainwater harvesting was a common technology that could act as a water supply in that period. However, as technology advanced, people started to build buildings and housing areas with water pipelines and reservoirs therefore rainwater harvesting technology stagnated during the following centuries. Despite that, rainwater harvesting technologies are still needed in many places with climate issues and a low or shortage of water supply.

In recent decades, rainwater harvesting technology has become more advanced worldwide, and it has been implemented in different sectors such as agriculture, and households. For instance, in the United Kingdom, many nurseries use water butts to harvest rainwater to keep the plants healthy by providing ample moisture during the monsoon period. On the other hand, climate change is also one factor that led people to start implementing RWHS. Due to climate change, the weather began to be unpredictable, floods or droughts could happen unexpectedly. Malaysia had a significant water shortage in 1998 (Sairi, Zain and Tahir, 2009), which was caused by the occurrence of drought due to climate change. As a result, Lembah Klang became one of the most vulnerable areas affected by the water issue. During that period of time, the State Water Board had to manage the water supply to ensure all residences had sufficient water supply. The government has outlined some of the methods employed to combat water scarcity, and rainwater harvesting is listed as one of the methods (Sairi, Zain and Tahir, 2009). However, the adoption of this technology was halted due to a lack of understanding amongst the public. In addition, severe floods in vulnerable areas have also led to sudden shortages of water supply, such as the incident which took place at Taman Sri Muda, Klang in December 2021. It happened due to unpredicted, continuously heavy rain in three days. The unpredictable weather could affect water resources utilisation for various sectors, especially in the agricultural industry. The climate change issue causes public concern on water conservation, especially when the government increases the price of water usage. Most of the public started to have the consensus in conserving rainwater for various purposes as rainwater can be reused and save the water bills in the long term.

These days, environmental protection activities under themes such as "Reduce, Reuse and Recycle" and "Conserve Water" are popular among the public. Therefore, many countries have started to enhance the implementation of rainwater harvesting technologies to solve environmental, social, and climate issues related to water usage. RWHS are one of the critical technologies which enable the public to assist in reducing freshwater consumption while restoring our natural environment. RWHS is a beneficial technology, especially in challenging geo-hydrological areas, where water supply is scarce. Therefore, the best solution is to collect rainwater and reuse it.

1.2 Importance of the Study

Rainwater harvesting technology is suitable for rich rainfall countries, such as Malaysia, Bangladesh, Indonesia, and Colombia. These countries had an average annual rainfall of approximately 2000 to 3000 mm. Malaysia is a tropical country abundant in water resources with an average yearly rainfall of 2400 to 2600 mm, and rainwater harvesting technology has existed in Malaysia for more than ten years. However, it is still not widely used in Malaysia due to the different policies implemented by the various state governments, and thus project planning is needed to ensure proper compliance suited to different rules and regulations. As a result, some states have implemented RWHS, but some have not. It is also rare for urban farmers to apply rainwater harvesting technology in Malaysia's urban farming as the Malaysian government prioritises the RWHS as a substitute resource in order to reduce dependency on surface waters (Lani, Yusop and Syafiuddin, 2018). On the other hand, since the pH of rainwater is usually quite acidic ($pH < 4.5$) in most industrial or urban areas, many prefer to use freshwater as the water tariff in Malaysia is relatively low (Shaari et al., 2008). Therefore, implementing a RWHS would lead to higher capital costs, since urban farmers will be required to treat the rainwater to an acceptable pH so that it can be used for irrigation purposes. Nonetheless if rainwater is not adequately utilised, it is anticipated that Malaysia could suffer from water scarcity due to population growth and water resource depletion during droughts. Since Malaysia is endowed with rich rainfall, a RWHS is an alternative water source for the public to get water supply. It is suitable for domestic and non-domestic use, especially when there is a water shortage. For instance, water supply shortages are common in the state of Selangor due to episodes of electrical failure at the pump house (Farah Solhi, 2022). Therefore, RWHS should be implemented to prevent the residents who stay in the Selangor area from facing difficulties in the water supply. The government can popularise the RWHS by encouraging the public with campaigns and subsidies.

Besides, the research data from the World Bank Group stated the agriculture sector occupied approximately an average of 70% of freshwater (Rome, 2017). The global demand for water consumption in the agriculture sector is expected to increase continuously by 50% by 2050 (Rome, 2017) to irrigate crops as agriculture is one of the sources of national prosperity and the supply for food production. As the world population grows, the demand for food production increases too, which leads to higher water consumption in the agricultural sector. To reduce freshwater consumption in agriculture, the RWHS is a good approach.

1.3 Problem Statement

Based on the World Health Organisation (WHO) report, clean drinking water is inaccessible to over 2.1 billion people in their homes, and 4.5

billion of them do not have proper sanitation in the world (WHO and UNICEF, 2017). Although some countries, such as East America, have access to water for daily activities, residents are required to travel a few kilometres just to access water sources. This would negatively impact their health in the long term as water is usually collected by women or children. Long walking distances could cause a huge physical burden on their health. In addition, water scarcity reduces their water ration while increasing the risk of contracting cholera diseases through the use of unsafe water sources for drinking and hygiene. On the other hand, hydrological systems and changes in weather patterns caused by climate change will significantly decrease water resource availability in countries such as Southeast Asia because their water source depends on surface water (Payus et al., 2020). Global warming has expedited and exacerbated the world's water cycle due to human activities, especially in rapid urbanisation, the use of fossil fuels, and etc. These human activities could lead to more climate change events such as floods, droughts, and storms (Mahmood, Jia and Zhu, 2019). Once the water cycle has been affected, the public would suffer without a clean water supply, especially in areas like Africa, because these areas are the least prepared to deal with climate change. Drought is expected to last longer and happen more frequently in central Europe and North America. Therefore, the RWHS is one of the possible solutions to improve water quality by collecting rainwater at home. However, the different climates in different countries could affect the amount of rainwater harvested by the RWHS.

This research study is focused on the design of an automated RWHS for urban agriculture in Malaysia. This technology is considered common in other countries such as Australia, North America, India, Japan and China. Although they had been implemented in their countries to increase the water supply, it was not commonly used in Malaysia in the 19th century due to a lack of awareness of this technology. By the 20th century, through the efforts made by the government, RWHS was implemented in a variety of constructions, such as residential and commercial buildings. Although the RWHS was used in some commercial buildings in Malaysia, an automated RWHS is not implemented in Malaysia with real-time monitoring for urban farming.

Monitoring the quality of rainwater was not a common practice as freshwater was always employed in urban agriculture. However, it is crucial to monitor the quality of harvested rainwater to determine if the quality of rainwater complies with the irrigation requirement. Therefore, a series of studies was conducted to propose an automated rainwater harvesting design for urban farming and to determine the water and cost saving potential with the installation of an automated RWHS. An automated RWHS could aid in monitoring the quality of rainwater and eliminate precipitation that does not fulfil the irrigation requirement. Consequently, it could assist farmers in reducing the amount of time they spend assessing the quality of rainwater and increase their productivity.

1.4 Aim and Objectives

This work aims to design an automated RWHS for sustainable urban agriculture. To achieve this aim, this following project objectives and activities will be carried out:

(i) To propose a minimal viable design of an automated RHWS with water quality control for urban agriculture
(ii) To estimate the water and cost saving potential of the automated RWHS
(iii) To evaluate the payback period of the system

1.5 Scope and Limitation of the Study

The scope of this study to design an automated RWHS for urban agriculture is focused on the investigation of several parameters such as the volume of rainwater harvested, the quality of rainwater by detecting its pH and electrical conductivity of rainwater and the water and cost-saving potential of the system. The quality of rainwater is critical because its usability is contingent upon the pH and electrical conductivity. Besides, the sensors considered for automation in this study are adequate to tackle problems like maintaining water quality of harvested rainwater such as pH level and electrical conductivity of harvested rainwater. In addition, the volume of rainwater harvested determines the amount of rainwater available for use daily or monthly. The amount of rainwater needed for plant irrigation was proposed based on only one type of crop, which is the chilli plant. No experimental work was done to estimate the amount of water needed for the chilli plant. Instead, the data was obtained through literature study. To summarise, the water-saving potential was evaluated based on the chilli plant, while the cost-saving potential was evaluated based on the volume of rainwater which could be harvested annually.

Moreover, there are some limitations in this study. Mesh filters were used to filter out big and small particles, however constant replacement of the fine mesh filter is required depending on the rainfall precipitation per month in order to maintain its efficiency. The gutters also require cleaning from time to time as big particles such as leaves might cause blockage of the gutters and obstruct rainwater flow into the catchment tank. In addition, there is only one prototype built in this study which was used interchangeably for the (1) first flush diverter design and (2) fine mesh filter design. Since there is a need of modify the system based on the designs, each design was used separately on different collection days. Therefore, it was not possible to run both designs simultaneously and perform a complete comparative study and analysis. To tackle this issue, period of study was extended to obtain more data points. Lastly, if maintenance of the prototype is required, a pressure washer is needed to clean the inner of PVC pipe, however maintenance is not taken into consideration in this study.

1.6 Contribution of the Study

In this study, an automated RWHS with a first flush diverter was proposed as a suitable design for urban agriculture. The Arduino Uno was used to interface between the sensors and the microcontroller. The sensors employed in the system ensured the quality of the rainwater was compliant with the irrigation requirement, while the SD module and reader allowed the users to obtain pH data during the rainy season. The findings of this study can serve as a framework for future studies and aim to apply in urban agriculture in Malaysia in order to reduce freshwater consumption.

1.7 Outline of the Report

This study was structured into five major chapters: introduction, literature review, methodology, results and discussion, conclusion and recommendations for future work. Chapter 1, the introduction briefly discussed the background of the RWHS, the importance of implementing a RWHS for urban agriculture, the problem statement of this study as well as the aim and objectives that aimed to tackle the problem throughout the study. The scope and limitations of this study were also discussed in Chapter 1.

Chapter 2, the literature review studied the global water usage phenomenon for domestic and non-domestic usage. The global perspective of RWHS as well as different designs and setups of RWHS were also explored in this study. There were two case studies discussed in this chapter which regard the integration of IoT with a RWHS.

Chapter 3, the methodology, a suitable work plan was proposed to conduct experimental studies in order to achieve the aim and objectives. The work plan included the material preparation, RWHS setup, sample collection and water quality analysis of rainwater and lastly the water demand for urban agriculture.

Chapter 4, results and discussion were discussed in this study in order to determine the feasibility of the automated RWHS for urban agriculture by evaluating the experimental results.

Lastly, Chapter 5, the conclusion summarises the findings of this study and also provides several recommendations for future work in order to enhance the proposed automated RWHS design.

CHAPTER 2

LITERATURE REVIEW

2.1 Global Water Usage Phenomenon

Water is an essential resource for all life and every sector, especially in global agriculture, because it is necessary to sustain the development of societies and the environment. Worldwide freshwater consumption has increased due to the rapid expansion of global population and economic development in various sectors such as industrial and agricultural. Global water consumption has risen approximately by 600% over the past centuries (Boretti and Rosa, 2019). Figure 2.1. illustrates the global freshwater consumption in 2014. Based on the data shown, the global agriculture sector is the sector that consumes approximately 72% of freshwater. In contrast, freshwater consumption is about 15% for industry, and domestic use is around 12%. By comparing the water consumption by region, it indicates that South Asia has the highest consumption, followed by Middle East and North Africa, Sub-Saharan Africa, Latin America and Caribbean, East Asia and Pacific and lastly Europe and Central Asia.

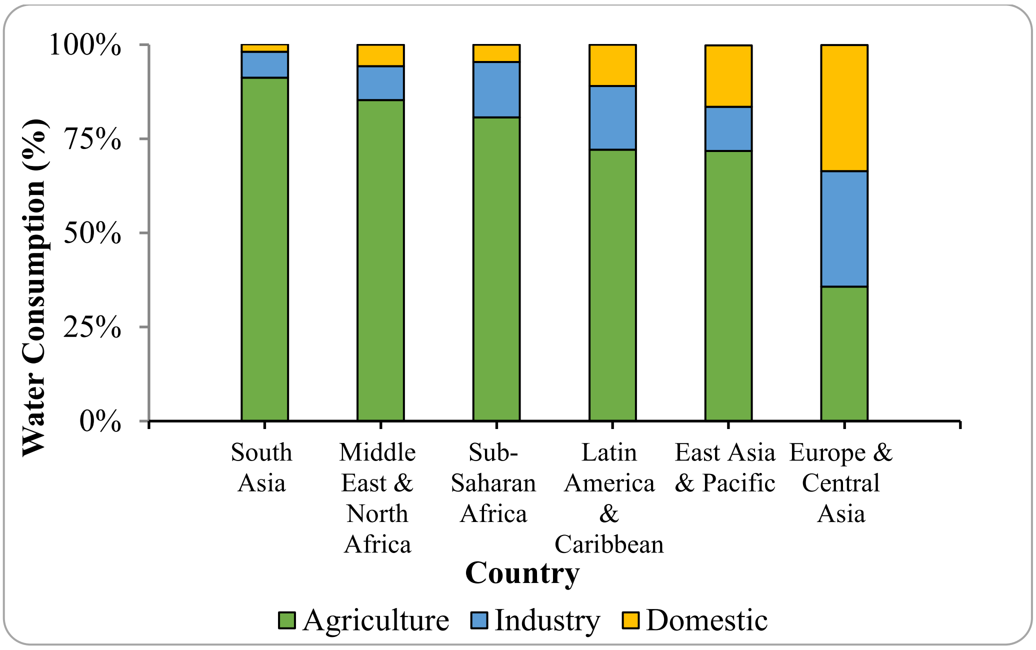


Figure 2.1: Global Freshwater Consumption in 2014 (Tariq Khokhar, 2017)

In future decades, global water consumption will continuously increase in all three sectors, including domestic, industry, and agriculture. Although industrial and domestic had significantly expanded faster than agricultural, the water consumption in agriculture will remain the highest. Currently, the global water consumption for all users is around 4,600 km^3 per year, however, it is anticipated to rise by 20% to 30% through 2050 which will reach approximately 5,000 to 6,000 km^3 per year (Boretti and Rosa, 2019). Figure 2.2 indicates the projected water consumption worldwide from 2014 to 2040. The global water consumption in the industrial and agricultural sectors is projected to increase approximately 20% to 21% from 2014 to 2040. As the worldwide population increases continuously in the future years, it would lead to higher food consumption. Therefore, water consumption in agriculture will increase significantly too. The agriculture sector rises around 10% every 15 years based on the data shown, while for the industrial sector is about 3% to 16%. However, water scarcity has been critical in the current decades.

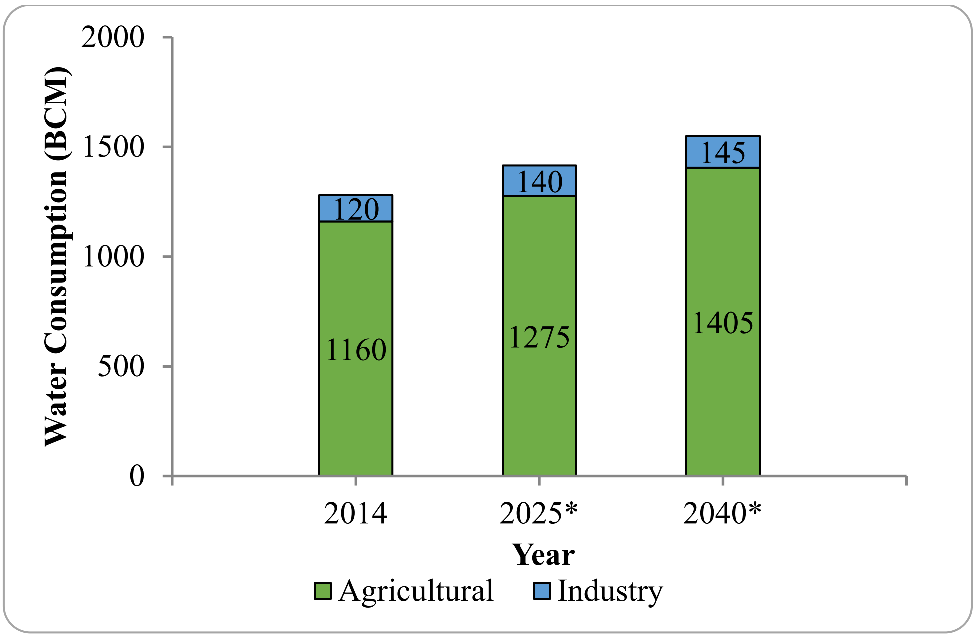


Figure 2.2: Projected Water Consumption Worldwide (billion cubic meters) from 2014 to 2040 (Statista, 2019)

2.1.1 General Use

Water is critical for daily indoor and outdoor activities such as drinking, washing, laundry, toilet usage, watering plants, and car washing. Malaysia is a country that is abundant in water however, the population growth, industrial developments, and irrigation in agriculture lead to high water consumption in the country. Therefore, the water demand phenomenon had shifted from being rich in water resources to water scarcity and had led to water pollution issues in the country. Based on the World Health Organisation requirement, the daily water usage per person should be 165 litres (L). However, based on the National Water Services Commission (SPAN) data, Malaysians consumed 201 L of water per day on average, which exceeds the requirement set. As Figure 2.3 illustrated, Malaysia's domestic metered water consumption was calculated at a billion L/d. It shows a significant increase in water consumption from 5.87 billion L of water per day to 7.17 billion L of water per day in the years from 2012 to 2020 (Statista, 2021).

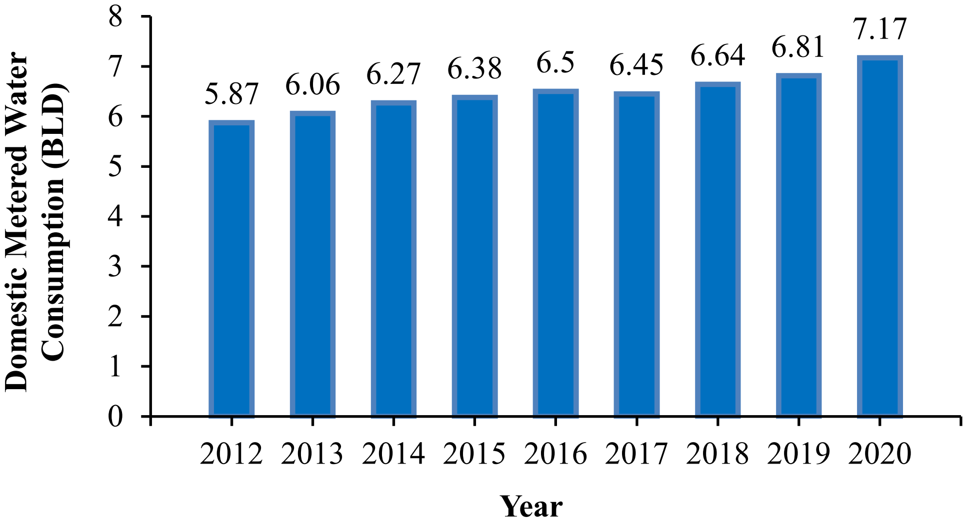


Figure 2.3: Domestic metered water consumption (billion litres per day) in Malaysia from 2012 to 2020 (Statista, 2021)

Besides, Figure 2.4 shows the water consumption of non-domestic usage in Malaysia from 2012 to 2020. Non-domestic water consumption represents the water usage in commercial institutions such as production lines, construction sites, offices, and agriculture. The data shows an increment of 1.03 billion L of water consumed per day from 2012 to 2019. However, water consumption has decreased by 0.37 billion L after 2019 as the commercial sectors were affected by the recent movement control order (MCO) (Department of Statistics Malaysia, 2021). MCO had restricted business operation hours and while some businesses were temporarily closed especially in the food service industry, and hence this has led to a decrease in water consumption.

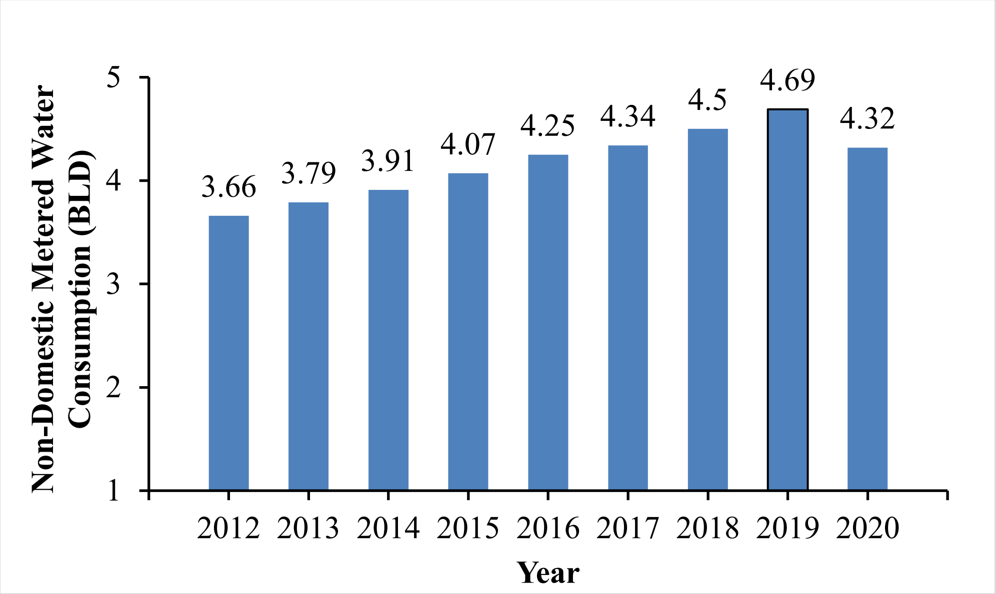


Figure 2.4: Non-domestic metered water consumption (billion litres per day) in Malaysia from 2012 to 2020 (Statista, 2022)

2.1.2 Agriculture Use

Water is utilised in various ways for livestock in agriculture, such as growing and feeding livelihoods, irrigation crops, and cleaning farming areas. Although there is minor water demand for livelihoods, the growing sector is rapidly increasing, and thus the water consumption also increases significantly. Irrigation is considered one of the most critical activities in agriculture as it is essential to grow and produce the various types of crops used for food production. Irrigation consumes over 60% of the freshwater worldwide, and approximately half of the freshwater supplied to irrigated fields run off to the ground or surface water sources. The other half of the water is lost due to evaporation, transpiration and some unintentional events such as pipe rupture.

Table 2.1 shows Malaysia's total agriculture water demand from 2010 to 2040. It indicated an increment of 9.5% for water demand in Malaysia agriculture from 2010 to 2020. The water demand in agriculture is usually used to sustain livestock, and for irrigation purposes. The water consumption is projected to decrease however, the water demand is still considered high.

Table 2.1: Agricultural Water Demand in Malaysia from 2010 to 2040 (Abdullah et al., 2016)

Year	**2010**	**2020**	**2030**	**2040**
Unit	**Million Cubic Meters**			
Total Agriculture Water Demand	9,511	10,415	9,438	9,169

For example, Florida, one of the constituent states in the United States, where the agricultural sector is the second largest industry in its state. Approximately 48% of groundwater is the water supply for the public, while 38% of water is used for irrigation in the farming industry (Borisova et al., 2019). Table 2.2 shows the irrigation demand in millions of gallons per day by crops from 2017 to 2040. The water consumption for irrigation is projected to increase by 3.14 % from 2017 to 2040.

Table 2.2: Irrigation Demand in Millions of Gallons Per Day by Crops from 2017 to 2040 (THE BALMORAL GROUP, 2019)

Statewide	**2017**	**2020**	**2025**	**2040**
Predominant Crop	**Average Millions of Gallons Per Day**			
Citrus	464	459	464	475
Field Crops	111	110	108	104
Fruit (Non-citrus)	69	67	67	68
Greenhouse	156	157	160	164
Hay	112	121	123	123
Potatoes	36	36	36	37

Sod	50	49	49	52
Sugarcane	654	654	635	632
Vegetable (Fresh market)	322	320	331	381
Total	1,974	1,973	1,973	2,036

2.2 Global Perspective of RWHS

Water scarcity is still one of the major impediments to economic development in many countries. In the hydrological cycle, rain is the primary source of water, whereas the rivers, groundwater or surface water are the secondary water sources. However, the public seems to forget that rain is the primary basis that sustains all of these secondary water sources in the present era. People started to rely on secondary water sources, leading to water scarcity issues. When climate change became the primary issue that caused insufficient water supply, people began to reconsider the use of rainwater. Therefore, many countries started to implement RWHS in different sectors, especially in agriculture, to reduce the usage of secondary water sources.

Rainwater harvesting is a technology that harvests rainwater directly from the roof, other catchment systems or the collection of sheets runoff from the artificial ground, natural surface for portable and non-portable use. Rainwater harvesting is a practice of maximising rainwater use where it falls to achieve self-sufficiency in water supply without relying on distant water sources. Besides, the system also contributes to food security and supplies water for agriculture use during the dry or monsoon period. Although not all rainwater can be collected, rainwater can also help in reducing the water consumption of the secondary water source. On the other hand, to ensure sustainable food production, rainwater usage has also become essential for the agriculture sector. If people continue to consume freshwater as the only source of water supply in agriculture, this could lead to water resources reaching an unsustainable level.

In recent years, rainwater harvesting has been brought back in South Korea as a practical approach for coping with extreme climate events, especially in urban areas with rapid development. The government in South

Korea encourages the public to implement the RWHS in their houses by offering incentive tools to the public. In addition, the Thai government also endorsed the low costs RWHS. Therefore, they launched a comprehensive national rainwater harvesting program by utilising the various capacities of jar tank systems from 0.1 to 0.3 m^3 (Musayev, Burgess and Mellor, 2018). The RWHS has been implemented in many areas for portable uses, and it has been shown that the collected rainwater allows the residents to use it for approximately six months during the summer months.

Moreover, a demonstration project on rainwater harvesting had been conducted in one of the provinces in China and came up with a positive result. Thus, the successful demonstration project had led to the construction of over 2 million rainwater reservoirs with an overall capacity of more than 70 million m^3. The results show that this amount of rainwater harvested can provide drinking water to nearly 2 million people and irrigate crops up to 200,000 hectares of land. Following the coming years, RWHS was implemented in 17 of China’s provinces in 2001, resulting in more than 5.5 million reservoirs as water supply. (Campisano et al., 2017)

Furthermore, the Taiwan Water Resources Agency had implemented a new policy by encouraging Taiwan’s citizens to install RWHS for domestic usage. The policy states that if the total area of the new building is more significant than 10,000 m^2, the public must implement a domestic RWHS that is capable of fulfilling at least 5% of the total amount of water needed in the building (Campisano et al., 2017). Apart from that, Sandakan, Malaysia, experienced a severe water shortage in 2000 due to climate change. One of the water sources for the water supplement system had decreased and affected the amount of water supply to the residents, and the State Water Board had distributed water for citizens in different areas of Sandakan. However, this is insufficient for them to use for daily activities such as cooking and washing. As a result, they published a rainwater policy implemented to remedy this issue and declared rainwater harvesting is compulsory for all households since the 1st June 2001.

2.3 Different Design and Setup of RWHS

There are various designs of RWHS however, not all types of harvesting systems can be applied in different topography of the region. Therefore, it is essential to select a suitable RWHS depending on the topography in order to achieve efficient harvesting of rainwater. These systems include water butt, indirect gravity, direct pumped with submersible or suction, retention ponds, ground storage, indirect pump, and gravity-fed (Team GSB, 2019). Although there are many types of RWHS, there are only two methods in harvesting rainwater which are rooftop harvesting and surface runoff rainwater harvesting. The basic components for a RWHS to be built are the catchment, conveyance, filter systems and storage tank.

2.3.1 Various Harvesting Methods

As mentioned in Chapter 2.3, there are two different methods of harvesting rainwater. Surface runoff harvesting is a method that allows rainwater to flow on the surface of the ground and store it into a storage tank for other water usage purposes. This method of rainwater harvesting is only applicable when there is excess rainfall because the loose soil would absorb the rainwater and allow excess rainwater to be collected. Besides that, the system is suitable to implement in urban areas as rainwater also can be collected, such as the pavement or rooftop. Therefore, if the system is installed near urban areas, excess rainwater will flow to the storage tank and act as a water supply after proper treatment and reduce freshwater consumption.

Surface runoff harvesting system includes rainwater collection tank, treatment system, purification, and storage tank. Figure 2.5 shows a scenario of surface runoff harvesting in urban areas. There are advantages and disadvantages in implementing this harvesting system. The advantage is that it could prevent soil erosion and urban flooding due to excess rain. The disadvantage is that it has high implementation costs, and the rainwater harvested might contain a lot of containments such as excess pesticides, heavy metals, etc. If the water is used for drinking purposes but not well-treated, it would harm human health. In addition, there are some challenges in implementing surface runoff harvesting systems. The challenges are it requires a proper treatment system to treat and remove the water’s impurities before reusing it. If a surface runoff harvesting system is designed and built nicely, it can capture huge precipitation and be an excellent substitute for fresh water supply. Apart from that, some reservoir capacities are small, which are unable to store a massive amount of rainwater therefore earthen bunds are a wise choice to limit the rainwater to runoff. A weir could control rainwater overflow when the storage tank is full.

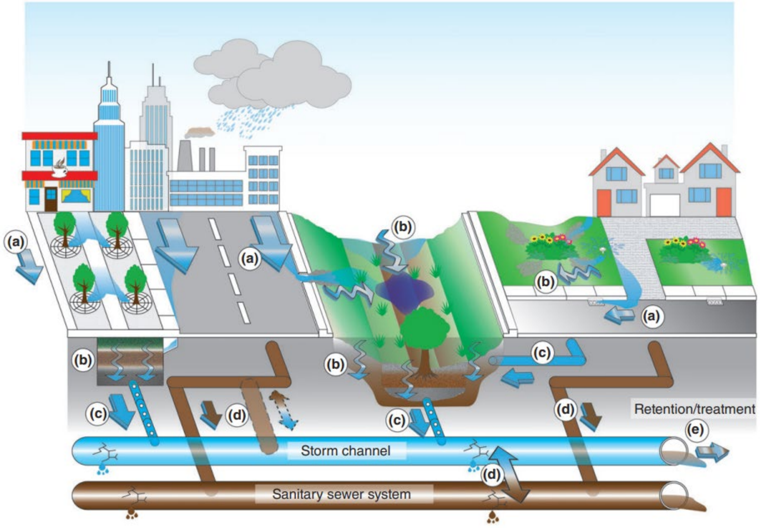


Figure 2.5: Surface Runoff Harvesting Scenarios (Jiang et al., 2015)

Moreover, rooftop rainwater harvesting is a method that harvests rainwater from the rooftop, and it flows through a gutter to a rooftop catchment area then conserved in a reservoir. Figure 2.6 illustrates a rooftop RWHS in a building. For this system, the rainwater is usually collected from the roof catchment area of residential, industrial and commercial structures and stored in a storage tank for various purposes. The harvested rainwater can also be stored in a subsurface groundwater tank using artificial recharge technology to satisfy the water demand of households or agriculture. This method is more direct than the surface runoff harvesting system as rainwater quality is better and environmentally benign. It can be applied in different regions and locations as it is easy to build and maintain.

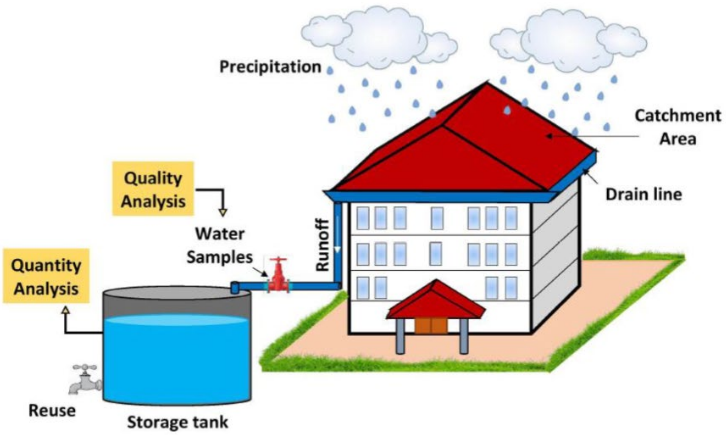


Figure 2.6: Rooftop Harvesting System (Anchan and Shiva Prasad, 2021)

2.3.2 Catchment System

There are three different catchment technologies: macro-catchment, micro catchment, and rooftop catchment. The main parameters needed to be considered in a catchment system are the characteristics of rainfall, runoff coefficient, size of the catchment area, and the amount of rainwater required to harvest. The macro-catchment technology is a system that utilises rainwater from huge areas such as hillsides, highways, and meadows. Earth or sand dams and rock catchments are examples of macro-catchment. It can be applied for various purposes such as irrigation and household use; however, farmers with limited resources usually will not install this system because it is more expensive than the micro-catchment system. The macro-catchment system is more complicated as the system needs to consider the parameters stated above. Also, the distance of rainwater can be transferred, and the type of soil consists in the rainwater collected.

In addition, a micro-catchment system is a system that harvests rainwater near crop growing areas and is used to recharge soil moisture. It is designed to gather surface runoff from small catchment areas and store rainwater to the nearby root zone of the infiltration area. The harvested rainwater is concentrated on a limited area where it was kept into the root area and supplied water for crops such as maise, millet, etc. The rainwater will be cycled within the crop’s growth area and the catchment area only, which reduces soil salinity and runoff precipitate. The size of this micro catchment system is approximately up to 1,000m^2 (Zhang, Carmi and Berliner, 2013).

This system is commonly used in small-scale agriculture because it is relatively affordable. In addition, it is also easier to build compared to the traditional irrigation method such as pulley system, chain pump and others. Farmers do not need to consume any freshwater to act as the water supply for irrigation purposes, therefore this helps to reduce the water tariff for the farmers. Nevertheless, there are some limitations on this catchment system due to the amount of harvested rainwater that is susceptible to evaporation.

Moreover, the main component for the rooftop catchment system is the material of the roof and the roof catchment area. There are many various types of material design of rooftop such as aluminium roof, concrete roof, and asbestos roof which can affect the quality of rainwater. The necessity of treatment of rainwater is determined on the quality of harvested rainwater. Table 2.3 shows the quality of rainwater from various roof types.

Table 2.3: Quality of Rainwater from Various Roof Types (Ayog, Dullah and Ramli, 2016)

Roof Type	**Turbidity (NTU)**	**pH**
Galvanised aluminium	96	6.4
Concrete tile	51	6.9
Green roof	4	6.5
Asbestos cement	0.6	6.6
Corrugated plastic	0.2	6.4

Based on the data illustrated in Table 2.3, different roof types could result in different values of pH, turbidity, and TSS. It indicated that the pH value of harvested rainwater from all roof types is within the range of 6 to 7. Nevertheless, there is a massive difference in the value of turbidity. The galvanised aluminium roof has the highest turbidity, while the corrugated plastic roof has the lowest. The turbidity value also depends on the contaminated materials on the roof type. For instance, if all of the roof types are in a new condition, the turbidity value might be lower because no contaminant would be flushed down by rainwater. In contrast, if the roof has aged, the turbidity value might be higher as the time passed would cause the degradation of the quality of the rooftop, and more contaminants would stay at the rooftop.

Nevertheless, rainwater is less contaminated, and it still requires little treatment before it is used for drinkable purposes. Based on the WHO standard, water pH should be 6.5 to 8.4, while it should be 5 or less for turbidity (Lani, Yusop and Syafiuddin, 2018). There are some limitations in installing a rooftop catchment system. The amount of harvested rainwater depends on the roof area. The larger the roof catchment area, the greater the amount of harvested rainwater. If the roof catchment system is applied in urban farming, it might require a larger roof area to harvest in order to substitute the freshwater supply for irrigation. In addition, the rooftop catchment system requires regular maintenance such as checking and repairing broken gutters, sweeping big particles and repairing pipe leakage.

Furthermore, in comparison to these catchment technologies, the macro-catchment system has relatively higher flow rates and runoff volume than the micro-catchment system therefore it requires larger pipelines and drainage control systems. However, the micro-catchment system could not handle high rainfall as the rainwater will be concentrated in a particular area, leading to flooding easily.

2.3.3 Treatment System

The treatment system is one of the most critical components in the RWHS. The setup of the treatment system and the treatment level depend on the purpose of water usage after harvesting rainwater. For instance, water used in agriculture for irrigation does not require much treatment than the water used for domestic applications. If the water is used for portable uses, it would require more treatment in order to fulfil the WHO standard. Filtration, chlorination, and flocculation are some of the treatments needed to ensure the harvested rainwater is clean and safe to drink.

Nevertheless, for agriculture use, there are some guidelines of water quality for irrigation to ensure the water does not affect the health of the crops. Table 2.4 shows the water quality standard for irrigation. Based on the guideline, the pH value for irrigation should be in the range of 6.5 to 8.4. On the other hand, there are five water quality classifications which are excellent, good, medium, and bad. The water quality is classified as excellent when the electrical conductivity of water is less than 250 micromhos per centimetre. Water quality is classified as very bad when the electrical conductivity value is more than 4000. While the range is more than 250 and less than 4000 would be classified as good, medium and bad respectively based on the value shown in the table. Water quality that does not meet the desired electrical conductivity and pH value should be treated until the value is in the acceptable range before use.

Table 2.4: Water Quality Standard for Irrigations (Arshad and Shakoor, 2017)

Water Quality Classification	**Salinity Hazard**	
	Electrical Conductivity at 25°C (micromhos/cm)	**Total Dissolved Solid, TDS (mg/L)**
Excellent	< 250	<160
Good	250-750	160 - 500
Medium	750 - 2250	500 - 1500
Bad	2250 – 4000	1500 - 2500
Very Bad	>4000	>2500
pH (Normal Range)	6.5 – 8.4	

Filtration is the standard treatment technique applied in RWHS. Filtration is considered a smaller scale version of screening. There are several stages of filtration, which are all measured in micron. For example, a one-micron filter can filter particles that humans could not see with naked eyes, and a 10-micron filter can filter out water particles that are 10 microns or larger. Dirt, microorganisms, or other suspended solid usually can be removed by undergoing filtration however, smaller particles such as bacteria can pass through filters therefore, further treatment is required to treat the bacteria. The advantage of having a filtration is that it is able to minimise the contaminant of chemical, microbiological and turbidity by different suspended solids (Latif, Alim and Rahman, 2022). Besides, disinfection is one of the techniques to kill microbiological bacteria that can inflict illness on humans. The primary disinfection procedures used in RWHS are chlorination and ultraviolet radiation (UV). Chlorination is a process of adding chlorine into the water to kill bacteria and viruses, and it can be any form of physical state. There are various types of chlorine disinfection categorised by different amounts of chlorine. Besides, the chlorination efficiency is determined by multiple parameters, including pH, water temperature, turbidity, contact time, and overall water quality (Latif, Alim and Rahman, 2022).The contact time is the amount of time required to react chlorine with untreated water. As the contact time increases, the efficiency of disinfection will increase. After adding chlorine into the water, it will form a residue and stay then keep the water disinfected. However, chlorine is a hazardous chemical therefore, the users should follow the guideline of chlorine treatment to ensure the amount of chlorine added will not cause harm to humans and the environment.

Moreover, ultraviolet radiation is an ultraviolet treatment that treats water by exposing the microorganisms to ultraviolet light, however, it does not remove them. Therefore, it is an effective method after filtering because filtration could not filter out all living organisms. In the ultraviolet disinfection process, the untreated water will be pumped into the system, passing through ultraviolet light. It will kill the bacteria and viruses, then water will be purified and leave the system. Ultraviolet disinfection is usually used with water filtration to supply clean water. The advantage of using this disinfection method is that it could kill microorganisms effectively without using any chemicals, and no water will be wasted in the treating process. While the disadvantage of using this system is that it requires a high temperature to disinfect the microorganisms and requires electricity to operate, it might be costly if a massive amount of water is needed to be treated.

2.3.4 First Flush Technology

First-flush technology is a technology that utilises a contraption that channels the first flow of rainfall in order to prevent the contaminant flow into the catchment tank (Rain Harvesting Pty Ltd, n.d.). The first flush diverter is commonly placed between gutters and the catchment system, therefore the suspended solid or pollutants would not flow into the catchment tank as well as storage tank. Besides, it is commonly used in rooftop RWHS as significant amounts of contaminants would be accumulated on the rooftop during the drying season. By installing the first flush diverter in the RWHS can improve the quality of harvested rainwater and minimise the number of suspended solids harvested as the rainwater will flush off the contaminant into the diverters at the beginning of rainfall. The accumulated contaminant that was commonly found on the rooftop was dead insects, dust, leaves, and heavy metals that came from the degraded quality of the rooftop.

Moreover, there are also advantages of installing a first flush diverter in the RWHS as it can reduce the counts of maintenance in the catchment tank as well as reduce the maintenance costs of the RWHS. In addition, the rainwater that is collected in the first flush diverter can be drained or used for other purposes such as washing or toilet flushing. Figure 2.7 shows the schematic diagram of the first flush diverter. The working principle of the first flush diverter is that rainwater will flush the suspended solid to the gutters, and the contaminant will flow into the first flush diverter. Then, the fine particles and suspended solid will be trapped in the downpipe. When the first flush diverter is filled with rainwater, the excess rainwater will start flowing into the tank.

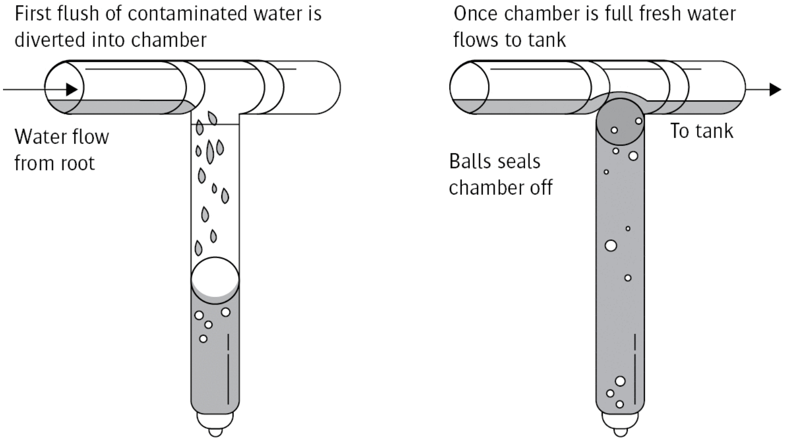


Figure 2.7: Schematic Diagram of the First Flush Diverter (Rain Harvesting Pty Ltd, n.d.)

2.4 Integration of IoT with RWHS

Internet of Things (IoT) is a device with network connectivity to sense and collect data and then send the information collected through the Internet. Wireless sensor networks (WSN) have recently gained substantial attention among researchers and industries. The principal goal for the research work and advanced development of wireless sensor networks is that they can be used in different sectors such as surveillance equipment, infrastructure inspection, and agriculture (Elhabyan, Shi and St-Hilaire, 2019). A proper design of a RWHS is necessary to include a large amount of data and analysis is required therefore, it is advantageous to implement an automated RWHS to enhance the system efficiency. Some of the case studies of smart RWHS have been studied and analysed.

2.4.1 Case Study 1

In this case study, Ranjan et al. proposed an integrative IoT approach for a smart RWHS. The smart RWHS, several microcontrollers included were the IoT controller, actuator, pH sensors, ultrasonic sensors, and rainfall sensors. Figure 2.8 shows the proposed RWHS by architecture.

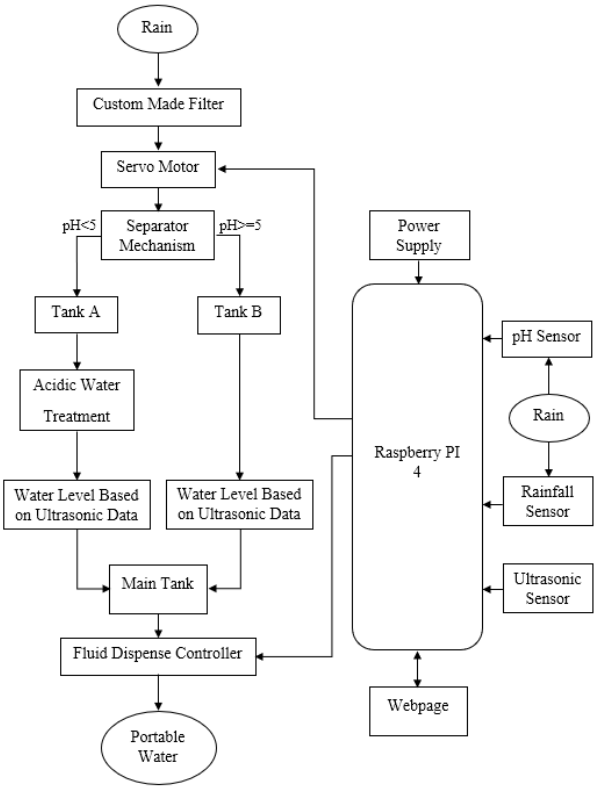


Figure 2.8: Proposed RWHS (Talari and Varun Jebakumar, 2021)

The proposed system activates with rain being detected by the rainfall sensor followed by the detection of rainwater pH via the pH sensor. Raspberry PI 4 calculates the acidity of rainwater, and sends out the data to the PC. Raspberry PI 4 is known as an IoT controller and a tiny computer system that can perform different tasks commanded by the users. In addition, there is a separator mechanism in this harvesting system that separates the rainwater into two different tanks, Tank A and Tank B. Tank A stores the rainwater below pH 5, while Tank B stores the rainwater that above pH 5. The storage capacity of both of the tanks is 5 L, and ultrasonic sensors are connected with both tanks used to detect the water level to ensure the water flows in does not exceed the tank capacity. An ultrasonic sensor detects water level, records the data, and then transfers it into the controller. Next, if the rainwater is detected below pH 5, it flows into Tank A, while if the rainwater is detected above pH 5, it flows into Tank B. Before the rainwater flows into both tanks, a filter filters out big particles such as leaves and sand. Besides, for Tank A, a container containing sodium hydroxide and soda ash is used to treat acid rain.

In contrast, for tank B, there is no treatment needed on the harvested rainwater to be done because the pH value of rainwater is nearly neutral. The entire treating process only took up to five minutes which is considered a fast-treating process. After treating the acid rain in Tank A, the water flows into the main tank, while for Tank B, the water flows directly into the main tank after filtering big particles. The storage capacity for the main tank is 50 L, and an ultrasonic sensor is also attached to the tank to detect the water level. The main tank output is connected with an automated water dispensary kit that allows excess water to flow out and maintains the water level in the main tank. The entire harvesting process is estimated to take up approximately half-hours to complete on average; however, if there is an error in the system, it might take up to 1 h to complete. (Talari and Varun Jebakumar, 2021)

2.4.2 Case Study 2

The proposed model in this case study is a solar-based RWHS. The purpose of this model is to determine the most effective methods of monitoring rainwater and evaluating data by using IoT. A test run was carried out in this case study in order to find out the accuracy of the flow sensor. The ThingSpeak website employs a cloud platform to gather information in order to boost the capacity of ground storage. Figure 2.9 shows the block flow diagram of this harvesting system. It illustrates the process of harvesting the system and the components used in the prototype. The solar panel harvests electricity for power supply in this system. Additionally, a flow sensor and a LCD were attached to the Arduino board for water flow control and data display. The solar panel is connected to a solar charge controller, and a bus trip is connected to a buck converter to activate the programmed controller. This case study scenario uses a rooftop to harvest rainwater, then it flowed pass a flow sensor through a pipe which gathered rainwater in an underground pit. The water was recycled into a tank using a submersible pump in the pit, and the output water flow data was displayed and recorded on the ThingSpeak website. The harvested water in the pit passed through an IoT module, Arduino with ESP8266 WIFI module.

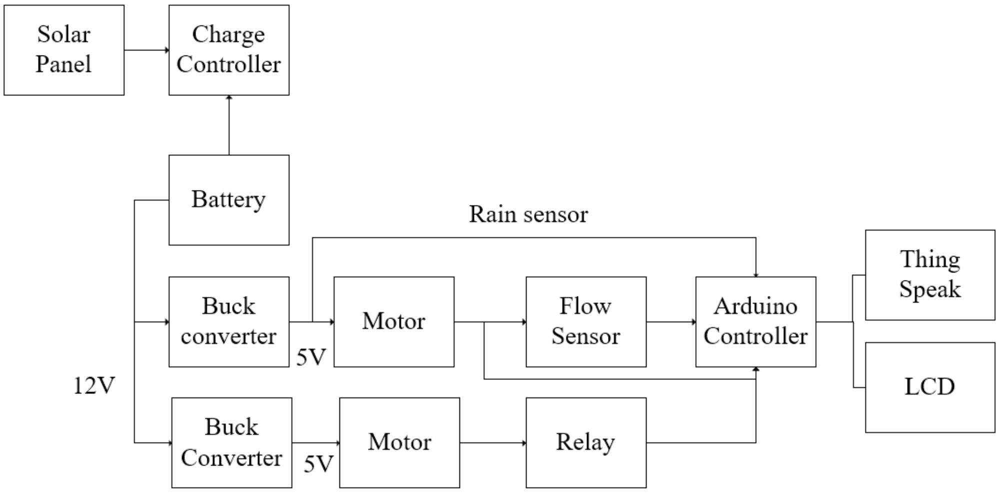


Figure 2.9: Block Flow Diagram of Solar Based Rainwater Harvesting Monitoring Using IoT (Chandrika Kota et al., 2020)

Moreover, the results were recorded through the ThingSpeak website for the test run of the harvesting system. Table 2.5 shows the accuracy analysis of flow sensors with discharge collected. The cloud provided two sets of data which is the total water flow in L and the water flow rate in litres per minute. The acquired data was evaluated using a qualitative methodology in the cloud gathered into a tank with time duration. The time of rainfall for prototypes was 1 min in the trials run in the case study. The collected rate of rainwater in the tank is different from the data detected by the flow sensor. There was some error on the flow sensor in measuring the data. However, the error was approximately 3%. The average accuracy of the flow sensor to harvested water is 97.47%.

Table 2.5: Accuracy Analysis of Flow Sensor with Discharged Collected (Chandrika Kota et al., 2020)

Height of the water column (cm)	**Collected rate of rainwater in tank**	**Measured rainwater through flow sensor**	**Accuracy (%)**
10	9	8.73	97
9.5	8.55	8.41	98.37
10.2	9.18	8.93	97.28

9.7	8.73	8.49	97.26
Average Accuracy of Flow Sensor			97.47

2.5 Challenges in Implementing RWHS in Malaysia

There are some challenges in implementing RWHS in Malaysia related to costs, uses of sustainable materials, treatment system, policy implementation, and enhancing public perception. Cost is one of the main challenges of implementing a RWHS regardless of which region, especially for farmers and citizens with low income. Even though the water bill in Malaysia is one of the lowest compared to other countries such as Indonesia and Singapore, the implementation costs are estimated to be around RM 1,600 to RM 12,600. In addition, farmers with low income usually will not be willing to adopt RWHS due to unfavourable return on investment. Therefore, the government could consider offering subsidies as an initiative or incentive to support and encourage the public to adopt a RWHS. (Lani, Yusop and Syafiuddin, 2018)

Besides, another challenge is that the public lacks knowledge regarding the critical RWHS. Although the government has taken the initiative to promote the RWHS, there is still a vast population of people who are not aware of the importance of water. This is because the water tariff is low therefore, people do not have the awareness to save water while consuming or implementing RWHS. Based on the Air Selangor data, the water tariff for Malaysian domestic users in Kuala Lumpur and the Putrajaya area ranges from RM 0.57 to RM 2 per metric cube of water, depending on how much water is consumed (Air Selangor, 2022). In contrast, for other countries such as Singapore, Tokyo, Dubai and New York, the average costs of water tariff are RM 10, RM 8.4, RM 10.08 and RM 13.02 per thousand litres of water, respectively (Lani, Yusop and Syafiuddin, 2018). In addition, Malaysia is a country with only a few instances of several droughts. It gives the public a mindset that it is not necessary to discover an alternative water source. Therefore, it leads to high water consumption stated in Chapter 2.1.

The government plays a vital role in restricting the public's water consumption. For example, the Singapore government imposed a limit for water consumption for manufacturers. When the manufacturer exceeds the water consumption limit, they will be fined with penalties. The Malaysian government can also implement such rules to restrict water consumption. Besides, the government can also provide an incentive by offering a discount for the public or agriculture sector that implement RWHS. The government can organise awareness campaigns to raise the public's interest and enhance the public perception of implementing this RWHS.

Giving penalties and offering subsidies are critical to fully adopt the RWHS in different sectors, especially households and industries. In fact, the Malaysian government has implemented a policy for the RWHS however, it has primarily been limited to specific building structures such as bungalows and public infrastructure. The Department of Irrigation and Drainage (DID) in Malaysia encouraged RWHS projects for different building types. Table 2.6 shows the RWHS implemented in Kuala Lumpur and Selangor area by DID, Malaysia. Most of the tanks installed in different locations used high-density polyethylene, and the implementation costs are between the range RM 20,000 to RM 200,000 depending on tank capacity. (Lani, Yusop and Syafiuddin, 2018)

Table 2.6: RWHS Implemented by DID, Malaysia (Lani, Yusop and Syafiuddin, 2018)

Location	**Tank Category**	**Cost (RM)**
DID Office, HQ KL	Underground Tank	200,000
Bukit Indah Mosque, Ampang, Selangor	Underground Tank	200,000
Bungalow House, Bangi, Selangor	Underground Pipe Package	20,000
Terrace House, Gombak, Selangor	Above ground HDPE Tank	20,000

Moreover, the policy of the RWHS should be broadened to different building structures due to the advantages that it brings to the public. Regrettably, the current policy is still fairly lax in Malaysia as the policy did not state the minimum tank capacity required in proportion to the rooftop area. In addition, commercial structures are still exempted from this restriction. As a result, before establishing a legislative regulation for RWHS, more research should be conducted to study and determine the optimal tank capacity based on the different types of rooftop areas and the climate circumstance for the conceivable future.

Furthermore, the use of materials in RWHS is one of the challenges. The harvested rainwater is relatively clean however the roof structure can pollute it. The standard roof structure was aluminium, steel, and other heavy metals compound and coated with protective paints. It ensures the roof structure can extend its longevity and prevent leakage. However, these materials tend to rust over time and contaminate the harvested rainwater, which causes rainwater to become more acidic. As a result, the rainwater harvested would require further treatment before it can be used. On the other hand, the catchment water tank and storage tank will also deteriorate with long exposure to the elements over time (i.e. wind and rain). Nevertheless, it also depends on the material used for tanks. For instance, concrete, polyethylene, and galvanised steel usually deteriorate and cause water contamination. These materials could be replaced by using more eco-friendly materials such as bamboo or rattan to reduce the possibility of water contamination. Bamboo is a sustainable material for building constructions and it is affordable and has a higher compressive strength than other materials such as concrete. As a result, more research for material used in RWHS is critical therefore, the public could enhance their knowledge on choosing the material used in the system. At the same time, the public can also harvest a better quality of rainwater by using sustainable materials.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The experiment aims to design an automated RWHS. There were three different stages in the experiment which include the initial stage, planning and design and the commissioning stage. The initial stage was the preparation work needed, such as the procurement of materials and the draft for the design system. Planning and design include parameters considered in the system and research on coding for designing an automated RWHS. Lastly, the experimental stage was to build the prototype of the automated RWHS and operate the system to collect experimental data.

3.1.1 Material Preparation

The material and quantity needed to construct a RWHS was listed in Table 3.1.

Table 3.1: List of Materials and Quantity

Materials	**Quantity**
Arduino UNO Basic Starter Kit	1 set
Float Switch	1 pc
AC to DC Adapter	1 pc
Relay Switch 5V to 12V	2 pcs
Solenoid Valve	2 pcs
pH module and pH detector	1 set
Acrylic sheet	1 pc
PVC pipe	4 m
Mesh filter (2mm)	1 pc
Fine mesh filter	1 pc
Water tank 5 L	1 pc
Water tank 19 L	1 pc
SD module and SD card reader	1 set

3.2 RWHS Setup

There are several basic components that are considered essential parts of a RWHS which includes a roof catchment area, a catchment tank, a supporting collection system, and a storage tank. The roof catchment area is the area where the rainwater samples are collected, while a supporting collection system includes gutter and PVC pipes to transport the rainwater to the catchment tank. A storage tank is used to store qualified rainwater samples. In addition, a filter system is usually an additional option for a RWHS, however, if the harvested rainwater is mainly for irrigation purpose, a filter system is an essential components in a RWHS. Figure 3.1 shows the schematic diagram of the automated RWHS. In this case, two types of mitigation systems were utilised and compared in this study which is a first flush diverter and a fine mesh filter. The design details of the automated RWHS is discussed in Chapter 4.

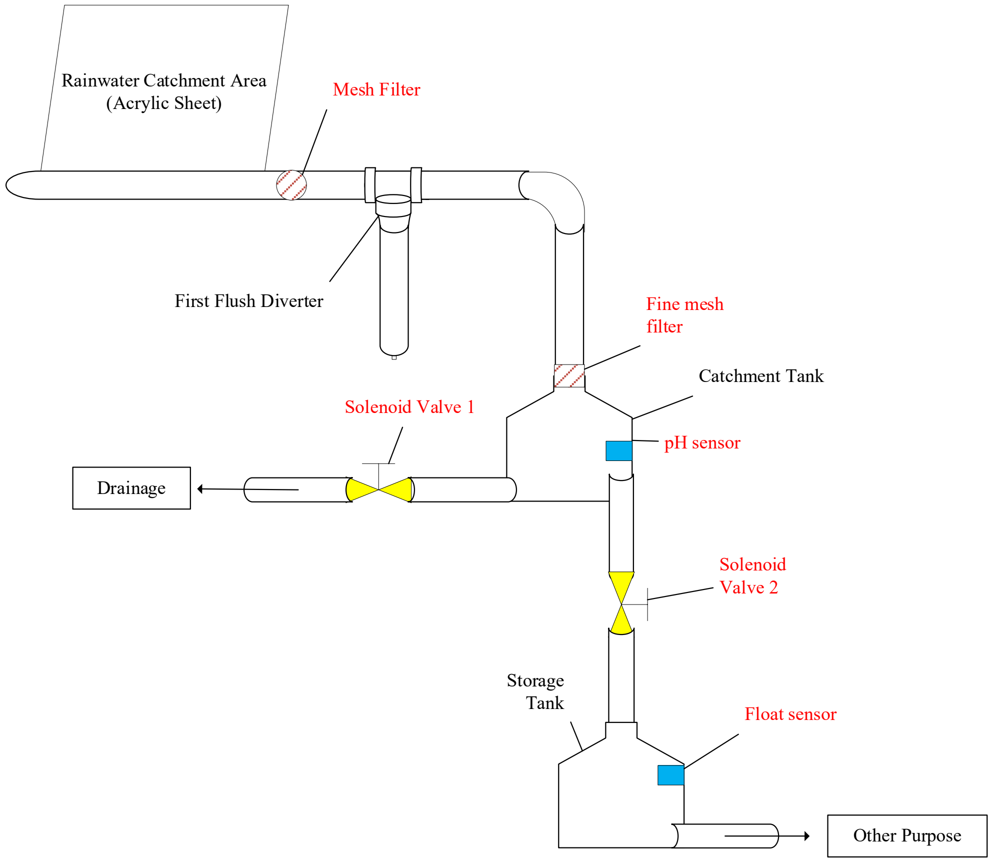


Figure 3.1: Schematic Diagram of Automated RWHS

3.2.1 Storage Tank

An acrylic sheet was used as the rooftop material to harvest rainwater in this study. This is because the quality of the acrylic sheet is similar to the material that used to build greenhouse roof. Both roofs have a smooth surface with a runoff coefficient between 0.8 to 0.9 (Nasif and Roslan, 2016). The rooftop surface area was calculated using Equation 3.1.

$$Rooftop\ Surface\ Area\ (m^2) = Length(m) \times Width\ (m) \qquad (3.1)$$

Figure 3.2 shows the area dimension of the rooftop. The size of the acrylic sheet is 12 in by 24 in. Therefore, the rooftop surface area is 288 in^2 which is equivalent to 0.186 m^2.

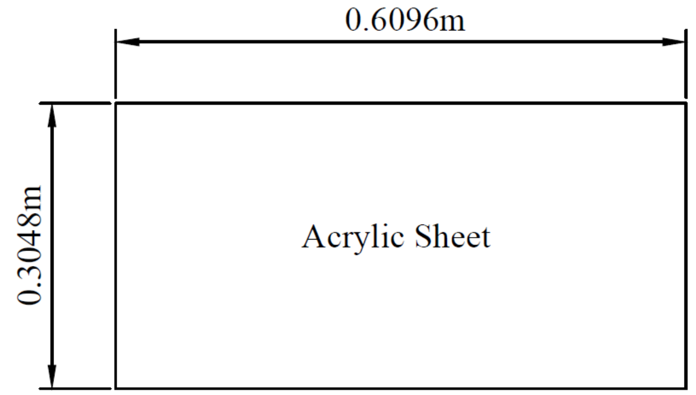


Figure 3.2: Area Dimension of Rooftop

Besides, the water harvesting potential obtained through Equation 3.2 was employed to calculate the amount of rainwater which can be harvested.

$$Amount\ of\ Rainwater\ Harvested\ \left(\frac{litres}{hours}\right) = Rooftop\ Surface\ Area\ (m^2) \times Rainfall\ \left(\frac{mm}{hours}\right) \times Runoff\ Coefficient \qquad (3.2)$$

The rainfall precipitation per day was calculated based on the annual rainfall and number of rainy days with Equation 3.3.

$$Rainfall\ per\ day\ \left(\frac{mm}{day}\right) = \frac{Rainfall\ per\ month\ \left(\frac{mm}{month}\right)}{Number\ of\ Rainy\ day\ \left(\frac{days}{month}\right)} \tag{3.3}$$

Therefore, the size of the storage tank was decided based on the calculated rainfall precipitation per day. Nevertheless, no data were obtained for actual rain hours per day, therefore an assumption was made in this case; the rain hours were assumed to be three per day. By making this assumption, the amount of rainwater harvested was calculated by using Equation 3.2. The rooftop area was based on the size of acrylic sheet, and the runoff coefficient was assumed to be 0.8, because the runoff coefficient for the smooth roof was found to be 0.8 to 0.9 based on literature (Nasif and Roslan, 2016).

3.3 Study Area

The study was carried out in Cheras, Malaysia. The location is based in a tropical country with an annual rainfall of 2400 to 2600 mm. In this study, the rainwater harvesting location was selected based on convenience, and the site chosen was Taman Cheras Utama, Malaysia, shown in Figure 3.3. The average annual relative humidity and rainfall data were obtained from Climate Data Org (2022).

Figure 3.3: Rainwater Harvesting Location

3.4 Sample Collection and Water Quality Analysis of Rainwater

The quality of rainwater is crucial, especially when it is used to irrigate plants in urban agriculture, as polluted rainwater would affect the growth of the plants and the crop yield. There are various factors that influence the quality of rainwater such as pH, soluble salts, and alkalinity. However, in this study, the investigation was focused on the pH and soluble salts of rainwater. The water quality standard for irrigation stipulates that high quality rainwater should have a pH between 6.5 to 8.4, and an electrical conductivity less than 250 ɥs/cm (Arshad and Shakoor, 2017). On the other hand, rainwater with an electrical conductivity more than 2250 ɥs/cm is considered bad quality. A high value of electrical conductivity in rainwater indicates that it has a high concentration of soluble salts, which may impede the absorption of nutrients and water by the roots of plants. In addition, for irrigating plants, a pH value that is less than 6.5 or more than 8.4 might inhibit the growth of plants; nevertheless, this would depend on the crop variety, and the soil acidity as each crop has its optimum pH value.

Moreover, the rainwater collection period was set as two weeks in this study, beginning on 29th June 2022 and ending on 13th July 2022. The pH and electrical conductivity were tested by using pH electrode E201-BNC and portable LCD EC with a temperature meter. The pH electrode was installed in the catchment tank and the rainwater sample was measured by the pH electrode immediately after rainwater was collected in the catchment tank to determine if the pH complies with the irrigation requirement. Then the qualified rainwater collected in the storage tank would be detected by the portable electrical conductivity meter after each collection day in order to determine if the quality meets the irrigation requirement too. In addition, if the pH of harvested rainwater in the catchment tank does not comply with the irrigation requirement, it will be discharged to the drainage through a solenoid valve.

3.5 Water Demand for Urban Farming

A literature study on chilli plants was conducted in order to estimate the water demand for urban agriculture. Chilli plants were chosen in this study because they are suitable to be planted in an urban garden with an optimal temperature between 20 °C to 32 °C (Jagdish, 2020). Besides, the pH and electrical conductivity requirements for planting chilli were also similar to the irrigation standard (refer to Table 2.4). The quality of rainwater is crucial, especially for irrigation purposes, because it determines crop productivity, crop health as well as the health of the soil. According to the research studies, if the pH of rainwater for irrigation is below 6.5 or above 8.4, it will extend the growing period of chilli plants as the chilli plants cannot absorb nutrients (Roshan Kumar, 2022). Nonetheless, many factors could affect the growth of the chilli plant such as soil type, and pest control, however the main focus in this study is the water demand for chilli plants to grow. Based on (Ikisian AgriInformation and Services, n.d.), the water required for irrigation in planting chilli was divided into several stages: nursery, transplanting, flowering, first pick up, and vegetable development and maturing. For each stage, the water required to irrigate chilli is 200 mm, 200 mm, 250 mm, and 400mm, respectively. Therefore, the total water needed for irrigating chilli is 1050 mm.

3.6 Water and Cost-saving Potential

The water needed for crop irrigation was calculated using Equation 3.4.

$$Water\ needed\ for\ irrigation\ \left(\frac{L}{day}\right) = \frac{Total\ water\ needed\ for\ irrigation\ (mm)}{Growing\ period\ (day)} \tag{3.4}$$

Subsequently, the water-saving potential was calculated based on the period of rainwater collection (day) using Equation 3.5.

$$Water\ saving\ potential\ (\%) = \frac{Rainwater\ harvested\ for\ \text{"x" no of}\ days\ \left(\frac{mm}{day}\right)}{Freshwater\ needed\ for\ irrigation\left(\frac{mm}{day}\right)} \tag{3.5}$$

On the other hand, cost-saving potential of a RWHS design was determined using Equation 3.6.

$$Cost\ saving\ potential\ \left(\frac{RM}{year}\right) = Water\ tariff\ \left(\frac{RM}{L}\right) \times$$
$$Volume\ of\ rainwater\ harvested\ \left(\frac{L}{year}\right) \tag{3.6}$$

3.7 Gantt Chart

Figure A.1 in the Appendix A shows the project activities that would be done in FYP 2. According to the Gantt chart, the RWHS prototype was built completely by Week 3. Several test runs were tested in the first three weeks in order to ensure the system can operate well, then only proceed to data collection for the automated RWHS. The data collection was completed within Week 3 to Week 7. In the meantime, report writing was started from Week 6 and was completed by Week 10. The amendment that required for the report in FYP 1 was completed within Week 6 to Week 10. The presentation slides and the poster were completed within Week 10 to Week 12.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Design of An Automated Rainwater Harvesting System (RWHS)

The subsections of Section 4.1 discuss the overall RWHS design including the sizing of storage tank, automation of RWHS and evaluation of the first flush diverter versus fine mesh filter. Several parameters were taken into consideration during the design of an automated RWHS. The design parameters include roof catchment area, volume of the first flush diverter, the size of the storage tank and the control system of the automated RWHS.

4.1.1 Sizing of Storage Tank

The storage tank size is one of the critical factors in the RWHS as it determines the volume of rainwater that can be stored and used during the dry season or for irrigation purposes. The annual rainfall precipitation data shown in Table 4.1 was used to estimate the size of the storage tank.

Table 4.1: Monthly rainfall data for Cheras, Kajang from January to December 2022 (Climate Data Org, 2022)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Rainfall (mm/month)	231	188	263	297	226	148	155	189	225	307	413	318
Rainy days (days/month)	15	13	17	19	18	16	16	17	18	19	20	18
Rainfall per day (mm/day)	15.40	14.46	15.47	15.63	12.56	9.25	9.69	11.12	12.50	16.16	20.65	17.67
Rainwater harvested (L/h)	2.58	2.42	2.59	2.62	2.10	1.55	1.62	1.86	2.09	2.70	3.46	2.96
Rainwater harvested in 3 hours (L)	7.73	7.26	7.77	7.85	6.31	4.65	4.87	5.58	6.28	8.11	10.37	8.87

According to the research data (Climate Data Org, 2022), the average annual relative humidity falls between 80 to 90 % in this region. Besides, Table 4.1 tabulated the monthly rainfall data for Cheras, Kajang from January to December 2022. Based on the data shown in Table 4.1, November has the highest relative humidity at 89.09% with an average of 20 days of rainfall precipitation, while February has the lowest relative humidity at 80.83% with an average of 13 days of precipitation.

The amount of rainwater which could be harvested per day was 4.65 L to 10.37 L. In the peak rainy season, it could harvest 10.37 L, while for the least rainfall period it could harvest 4.65 L of rainwater. Therefore, the minimum size of the storage tank was set as 10.37 L. Since used or commercially available large plastic containers are easily accessible and available in the market for reuse, thus it is chosen for this purpose and the size of storage tank used was 19 L. Figure 4.1 shows the storage tank that was used in the automated RWHS.

Figure 4.1: Storage Tank used in the Automated RWHS

4.1.2 Automation of RWHS

The implementation and operation of a RWHS are relatively simple. However, there was the effort required in order to maintain the entire system. An automated RWHS can perform rainwater harvesting with less variability than humans and resulting in better control and consistency of RWHS, despite the fact that the human can perform high-quality work. Therefore, an automated RWHS mounted with a microcontroller integrates several sensors for smart rainwater harvesting and enables the system to operate autonomously. With the aid of automation, the RWHS is able to help with data logging and histogram the rainfall collection data, and with these features, it allows the user to notice and diagnose the issue that may occur in the system. Generally, an automated RWHS allow real-time monitoring of rainwater harvesting status which brings conveniences to the users to monitor and control the system remotely. In addition, it is also able to automate the process of water storage and maximise the capacity of the storage tank. The sensors employed in the automated RWHS have the capability to determine and ensure the quality of rainwater complies with the irrigation requirement. The setup of automated RWHS would also trigger specific action signals according to the conditions of the automated system that are programmed by the users.

In this study, the system was designed to be gravity-fed automated RWHS. The system was designed to be a gravity-fed automated RWHS. The advantage of a gravity-fed harvesting system is that it does not require any water pump in the catchment tank to increase the water pressure and flow. The gravity-fed RWHS allows the rainwater to flow from the catchment tank to the storage tank by gravity. Therefore, the designed automated harvesting system could reduce its implementation costs and energy consumption. In addition, with the aid of an automated system, the automated RWHS could monitor and control the quality of rainwater harvested by determining if the quality of rainwater complies with the irrigation requirement. The quality of rainwater would be affected by the roof material and air quality. The poor water quality of rainwater would affect the crop, soil and human health and cause the low production of crops, therefore an automated RWHS is a good approach.

Several major components were assembled together to build an automated RWHS. Figure 4.2 shows the overview of the design of the automated RWHS.

Figure 4.2: Overview of the Design of an Automated RWHS

The design of an automated RWHS is comprised of three main parts: Part A, Part B and Part C. Figure 4.3, Figure 4.4, and Figure 4.5 illustrate each parts, respectively. Part A is comprised of an acrylic sheet that acted as the roof catchment area, a gutter that made up of PVC pipes acted as the supporting collection system and a first flush diverter was used to divert the first flush of the rainfall precipitation (Figure 4.3). The volume of the first flush diverter was designed to flush 0.5 L of rainfall precipitation since diverting 0.5 L of rainwater is sufficient to tackle minimal pollution of rainwater collected from a rooftop (open field with no trees) (Rain Harvesting Pty Ltd, n.d.).

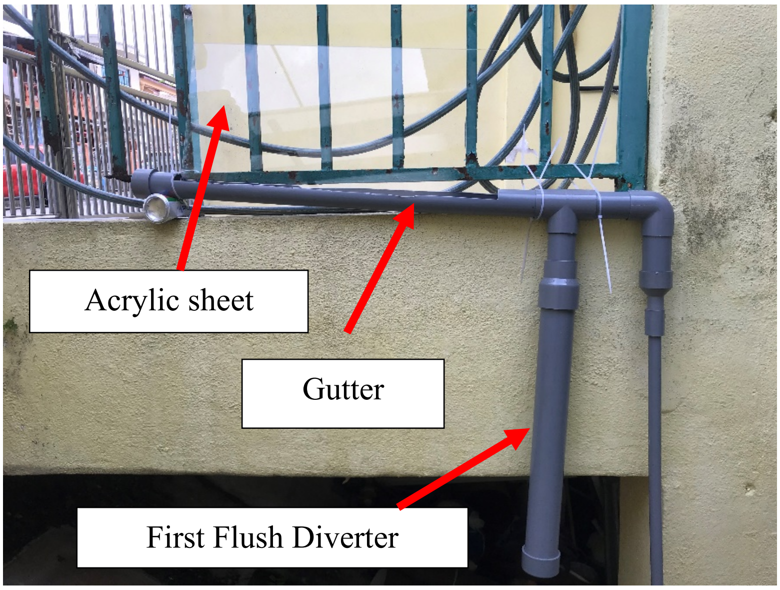


Figure 4.3: Roof Catchment Area of the Automated RWHS (Part A)

Furthermore, Part B of the harvesting system included a 5 L catchment tank, a fine mesh filter, a pH detector and two solenoid valves (Figure 4.4). The catchment tank was used to collect the harvested rainwater, while a fine mesh filter was employed to filter suspended solids during the rainy season. In addition, the pH detector was used to measure the pH of rainwater harvested in the catchment tank. If the pH does not comply with the irrigation requirement (> 6.5), solenoid valve 1 will discharge the harvested rainwater to drainage, however if the pH level meets the irrigation requirement, the solenoid valve 2 will convey the qualified rainwater to the storage tank. Part C of the harvesting system included a float sensor and storage tank. The float sensor was employed to measure the water level in the storage tank, and the storage tank was used to store qualified rainwater (Figure 4.5).

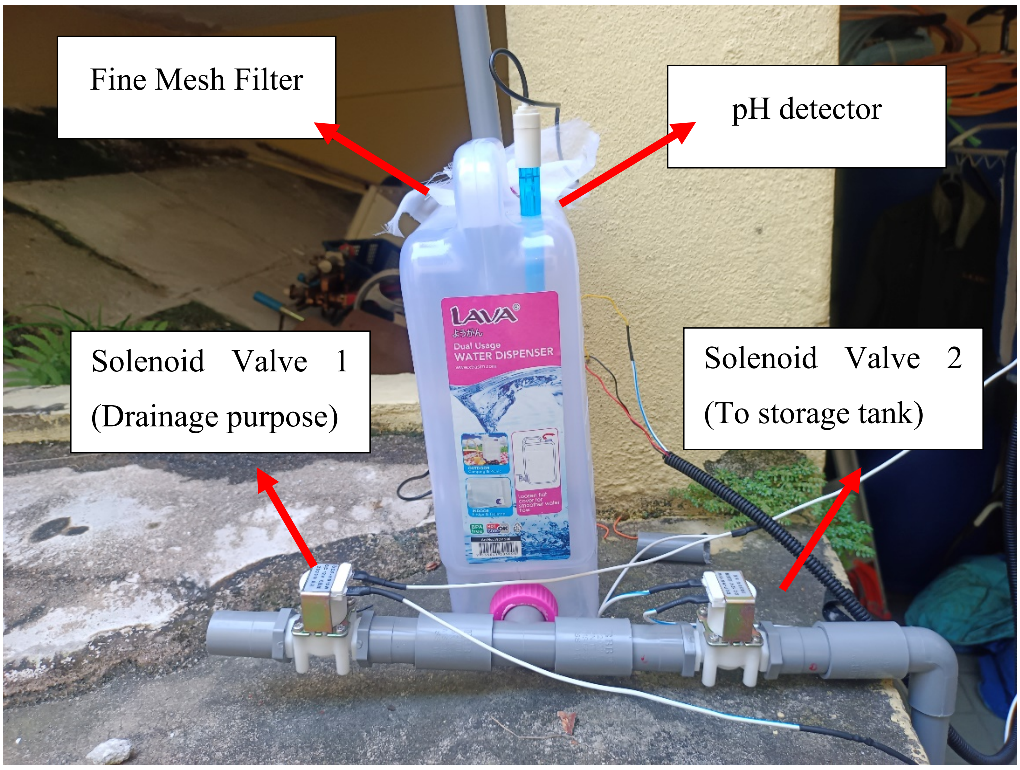


Figure 4.4: Catchment Tank of the Automated RWHS (Part B)

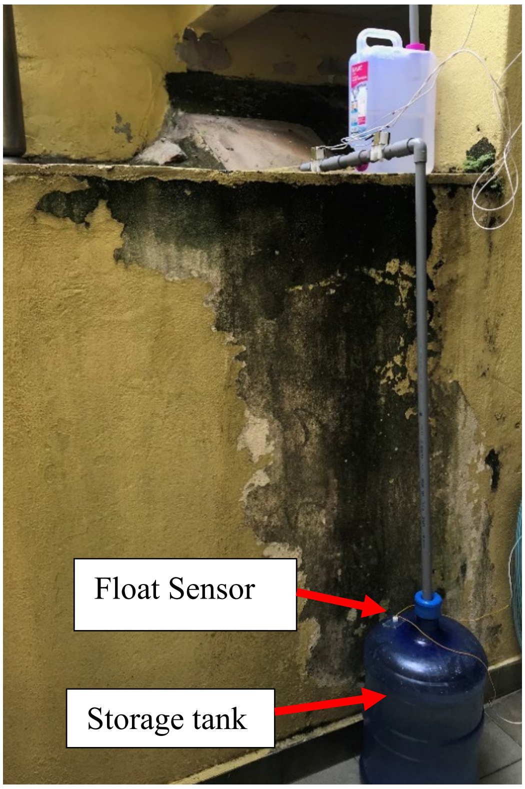


Figure 4.5: Storage Tank Setup of the Automated RWHS (Part C)

Figure 4.6 shows the wiring diagram of the RWHS using IoT. The computer connected with the Arduino microcontroller was used to upload the programmed codes for the RWHS. After uploading the programmed codes to the Arduino microcontroller, the harvesting system can be operated automatically with a 12V power supply during the rainy season. Figure 4.7 shows the paper box that was used to mount the components connected to the Arduino Uno and the components included such as an Arduino Uno SD card module, and two relays. Meanwhile, several sensors were also employed and connected to the microcontroller, which includes a float sensor, a pH module and two solenoid valves. Besides, on the other end of the pH module was connected to the pH probe. The pH probe was immersed in the catchment tank and the pH detector was able to detect pH of rainwater. The float sensor was employed to detect the water level in the storage tank. Alternatively, the wiring schematics shows that the relays of 5V to 12V were connected to the solenoid valve and a power supply in order to allow 12V of the solenoid valves to be powered by the microcontroller. There were two LEDs attached on the top of the paper box (Figure 4.7). The purpose of placing LED on the top of the box is to ensure the pH data of collected rainwater was recorded and stored in the SD card of the automated RWHS throughout the harvesting period. The LEDs served as an indicator to determine the status of the SD card. The red LED lights up when there is a faulty or missing SD card, whereas the green LED lights up to represent the SD card is in working condition.

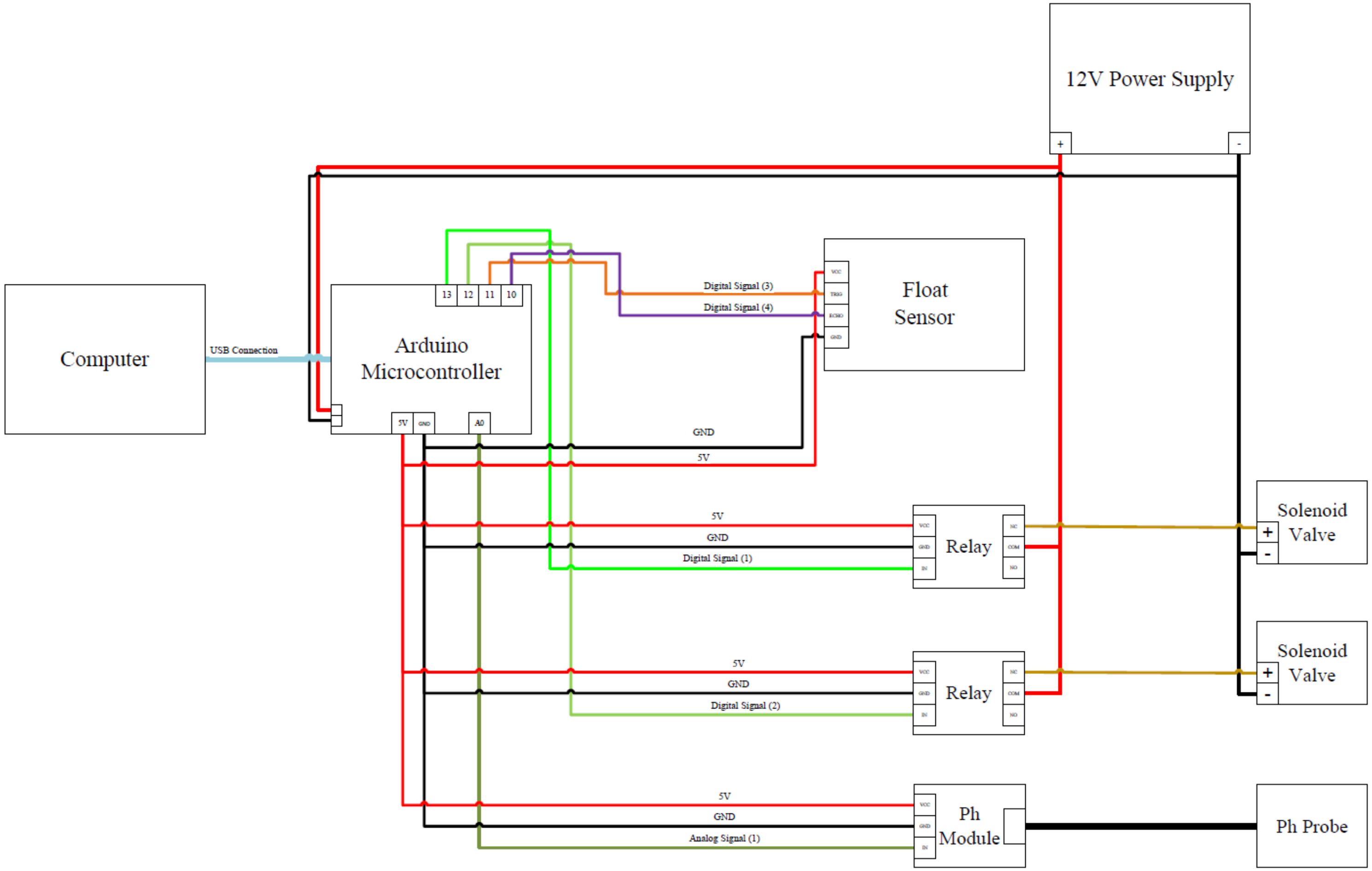


Figure 4.6: Wiring Diagram of RWHS using IoT

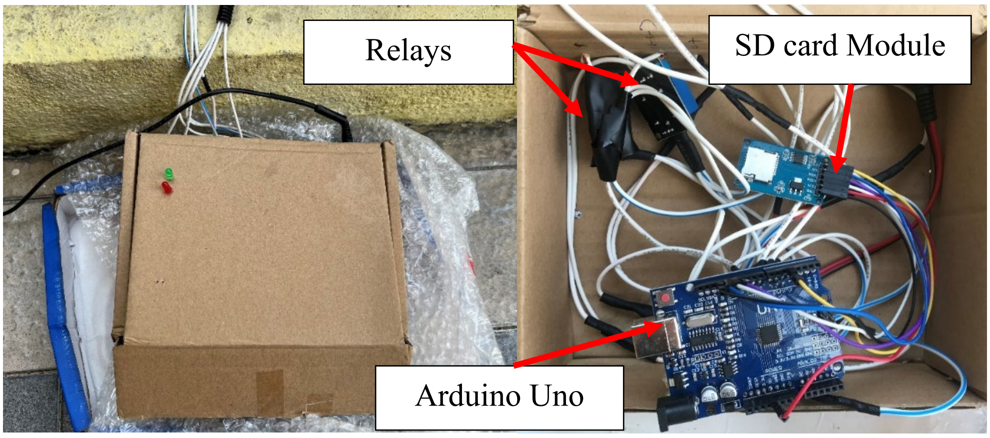


Figure 4.7: Mounting of Arduino Uno and Its Setup (Components Connected)

Figure 4.8 shows the flowchart diagram in the programming for the automated RWHS. The power supply of the system was switched on during the collection period. Besides, the figures in Appendix A illustrated all coding for the automated RWHS. Figure 4.9 shows the various declared and initialised variables as well as a built-in-setup function from Arduino. The LEDs pin and the switch that connected to the sensors were defined in the system, the sensors included float sensors, solenoid valves, and pH sensors. In addition, the float sensor was set as an input pull up resistor in order to increase its resistance to the pin. On the other hand, Figures 4.10, 4.11 and 4.12 show the loop function of the control system. The system would take six average values of the rainwater and record them in the SD card reader. The pH data was recorded in the file name “pH data”. Nonetheless, if there is a fault in reading the SD card, a red LED would showed and “initialization failed !” would be recorded in the file.

Furthermore, when the rainwater was collected to a certain level in the catchment tank during the rainy season, the pH detector would start to detect the pH of the rainwater. In order to acquire accurate results, the pH detector detected the middle level of harvested rainwater in the catchment tank. When the pH value was detected to be more than or equal to 6.5, the float sensor in the storage tank would start to detect the water level. If the water level is not in full condition, the solenoid valve 2 that was installed in the system would open and transport the harvested rainwater into the storage tank. Vice versa, if the water level in the storage tank was detected as full condition, solenoid valve 2 would close in order to prevent leakage of the storage tank. Then, the automated RWHS would start to detect the pH of harvested rainwater in the catchment tank again. Besides, if the harvested rainwater in the catchment tank was detected to be less than 6.5, therefore the solenoid valve 1 that was installed on the other side of the catchment tank will open and drain out the rainwater for 3 minutes in order to remove all harvested rainwater in the catchment tank.

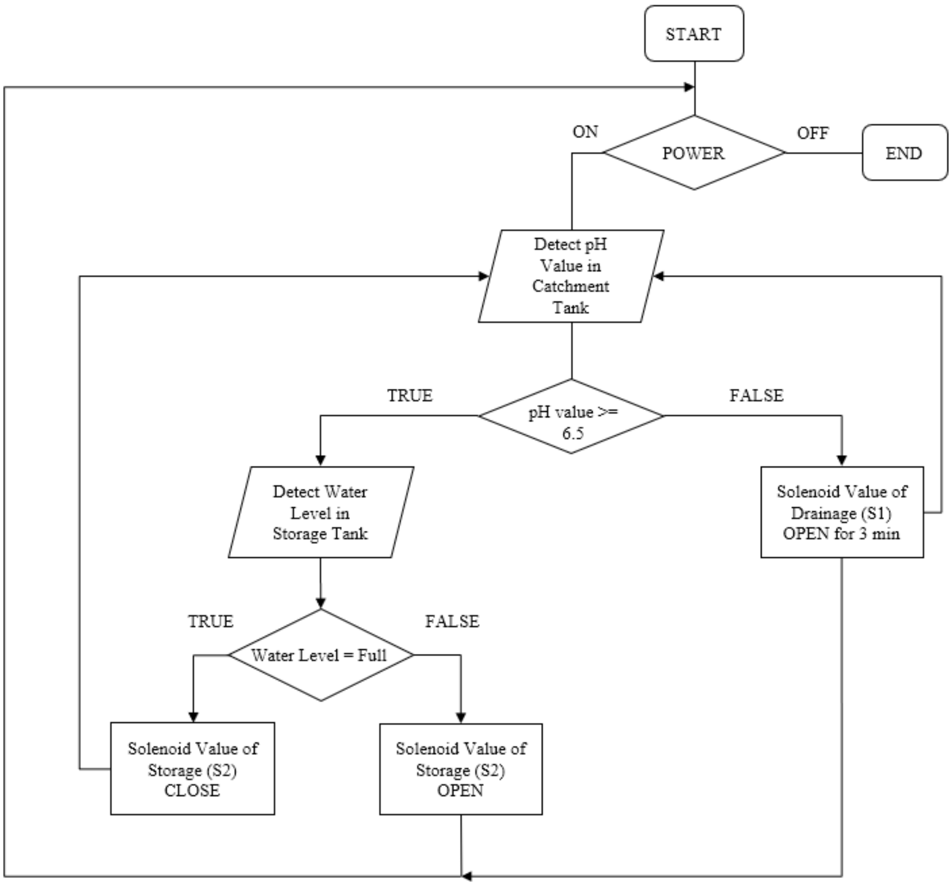
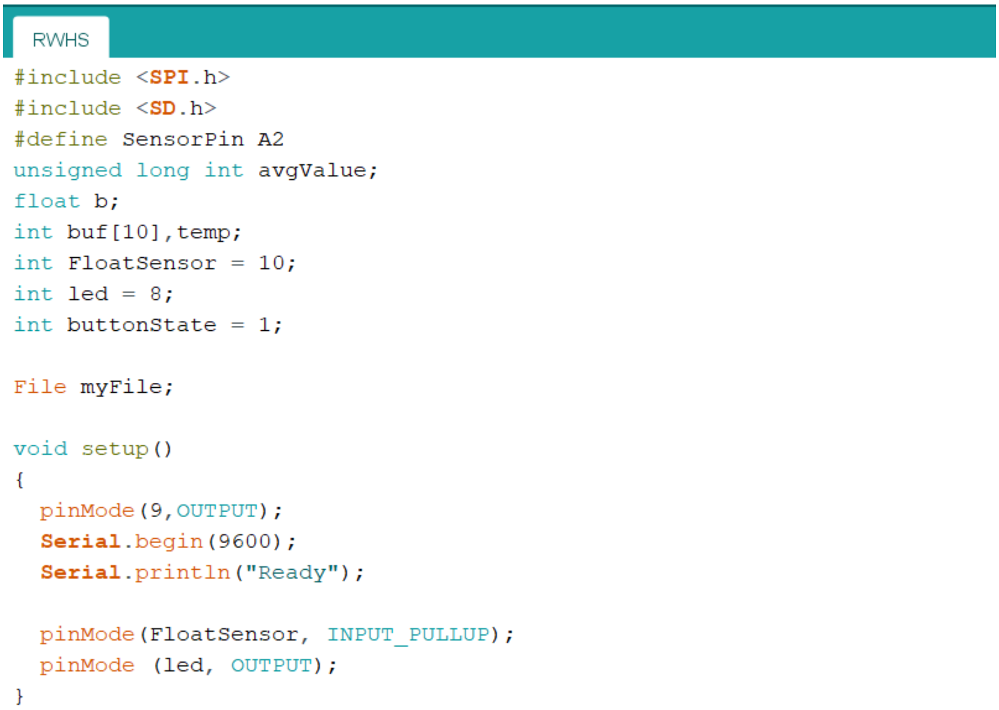


Figure 4.8: Flow Chart Diagram in Programming for RWHS

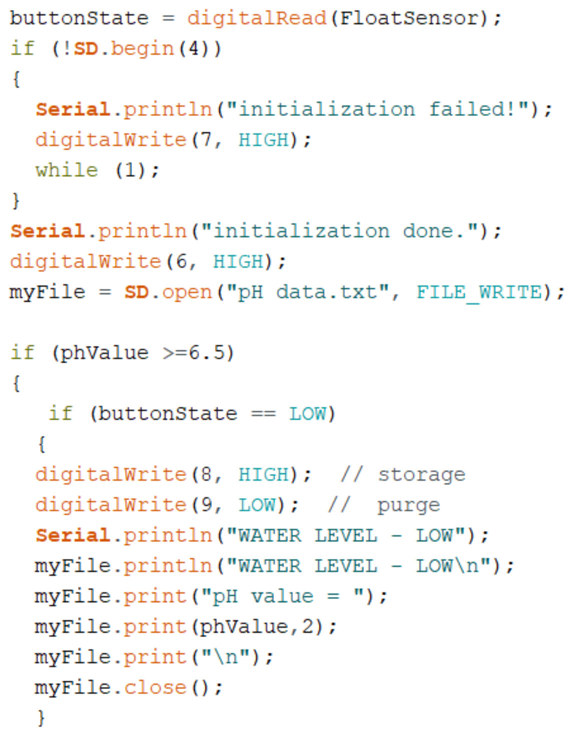


```
#include <SPI.h>
#include <SD.h>
#define SensorPin A2
unsigned long int avgValue;
float b;
int buf[10],temp;
int FloatSensor = 10;
int led = 8;
int buttonState = 1;

File myFile;

void setup()
{
  pinMode(9,OUTPUT);
  Serial.begin(9600);
  Serial.println("Ready");

  pinMode(FloatSensor, INPUT_PULLUP);
  pinMode (led, OUTPUT);
}
```

Figure 4.9: Various Declared, Initialised Variables and Built-in Setup Function

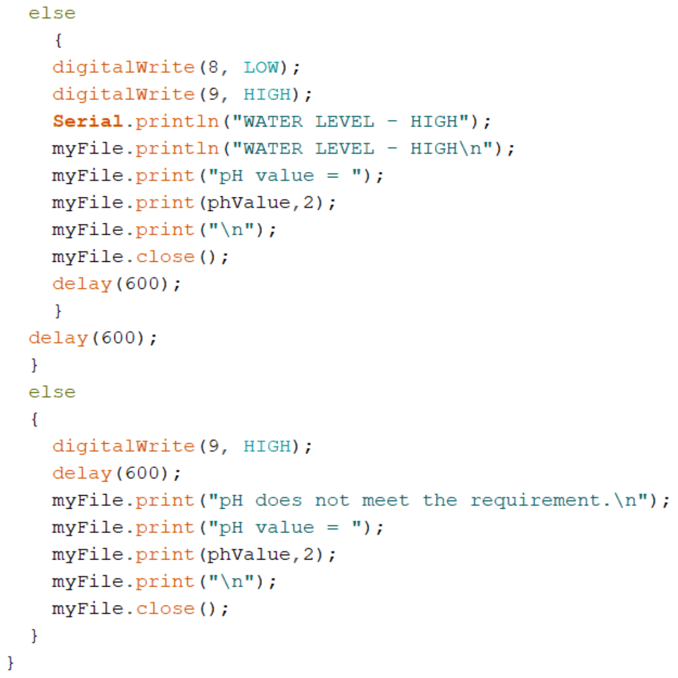
```
void loop()
{
  for(int i=0;i<10;i++)
  {
    buf[i]=analogRead(SensorPin);
    delay(10);
  }
  for(int i=0;i<9;i++)
  {
    for(int j=i+1;j<10;j++)
    {
      if(buf[i]>buf[j])
      {
        temp=buf[i];
        buf[i]=buf[j];
        buf[j]=temp;
      }
    }
  }
  avgValue=0;
  for(int i=2;i<8;i++)
    avgValue+=buf[i];
  float phValue=(float)avgValue*5.0/1024/6; //convert the analog into millivolt
  phValue=3.5*phValue;                      //convert the millivolt into pH value
  Serial.print("    pH:");
  Serial.print(phValue,2);
  Serial.println(" ");
```

Figure 4.10: Loop Function of the Control System (Part A)



```
buttonState = digitalRead(FloatSensor);
if (!SD.begin(4))
{
  Serial.println("initialization failed!");
  digitalWrite(7, HIGH);
  while (1);
}
Serial.println("initialization done.");
digitalWrite(6, HIGH);
myFile = SD.open("pH data.txt", FILE_WRITE);

if (phValue >=6.5)
{
   if (buttonState == LOW)
  {
  digitalWrite(8, HIGH);  // storage
  digitalWrite(9, LOW);  //  purge
  Serial.println("WATER LEVEL - LOW");
  myFile.println("WATER LEVEL - LOW\n");
  myFile.print("pH value = ");
  myFile.print(phValue,2);
  myFile.print("\n");
  myFile.close();
  }
```

Figure 4.11: Loop Function of the Control System (Part B)



```
  else
    {
    digitalWrite(8, LOW);
    digitalWrite(9, HIGH);
    Serial.println("WATER LEVEL - HIGH");
    myFile.println("WATER LEVEL - HIGH\n");
    myFile.print("pH value = ");
    myFile.print(phValue,2);
    myFile.print("\n");
    myFile.close();
    delay(600);
    }
  delay(600);
  }
  else
  {
    digitalWrite(9, HIGH);
    delay(600);
    myFile.print("pH does not meet the requirement.\n");
    myFile.print("pH value = ");
    myFile.print(phValue,2);
    myFile.print("\n");
    myFile.close();
  }
}
```

Figure 4.12: Loop Function of the Control System (Part C)

4.1.3 Evaluating RWHS Designs: First Flush Diverter versus Fine Mesh Filter

The harvested rainwater samples were collected using an automated RWHS. Two different designs were compared and studied to harvest rainwater: (1) system with a first flush diverter and (2) system with a fine mesh filter. The automated RWHS with a first flush diverter diverts the first flush of rainfall precipitation during the rainy season, whereas the automated RWHS with a fine mesh filter filters suspended solid before rainwater flows into the catchment tank. Besides, the electrical conductivity and pH of rainwater were one of the parameters that were considered before determining the usability of rainwater for irrigation purposes. Although rainwater is relatively clean, pH and electrical conductivity are required to test to ensure the rainwater meets the irrigation requirement (refer to Table 2.4). Thus, the pH of rainwater in the catchment tank would be recorded as well as the electrical conductivity of rainwater in the storage tank in this study.

There was a total of seven rainy days throughout the rainwater collection period from 29th June 2022 to 13th July 2022. Figure 4.13 shows the rainwater pH on different collection days. Six pH measurements were extracted from the data log and an average pH was calculated. Based on the results presented in Figure 4.13, the average pH value of rainwater harvested on Day 4 was 5.56 (acid rain), therefore the rainwater was not transferred into the storage tank. Instead, it was discharged automatically by the automated RWHS. On the other hand, the pH of rainwater for the other six collection days had met the irrigation requirement; therefore, they were stored in the storage tank.

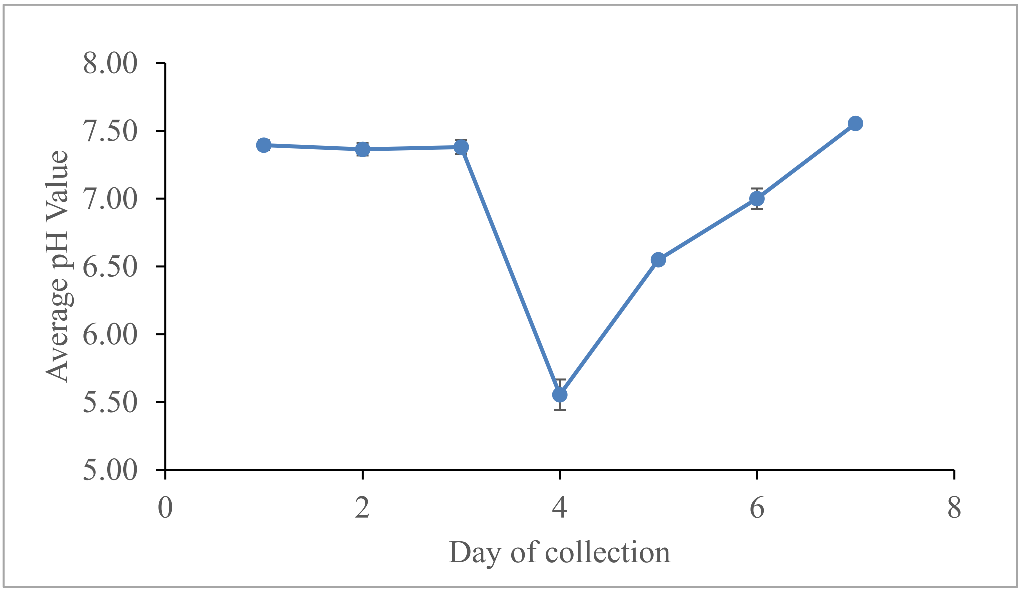


Figure 4.13: Rainwater pH on Different Collection Days

In addition, the water quality of rainwater is highly dependent on weather conditions such as the air quality index and wind speed. However, the air quality index is the key parameter that affects the quality of rainwater. Based on the research studies (Rahman et al., 2022), the air quality index is classified into five categories which include good, moderate, unhealthy, extremely unhealthy and hazardous. Table 4.2 shows the air quality index for each category. On top of the rainwater being tested as acidic on Day 4, the air quality was also relatively high at 102. This level of air quality index is categorised as unhealthy. When the water condenses, it interacts with various airborne chemicals in the air and dissolves them. Consequently, acid rain was formed as the rainwater accumulated additional pollutants. As a result of air pollution, rainfall precipitation becomes cloudy and acidic. Whereas, for other rainwater collection days, the air quality index was under moderate conditions which were approximately 85 to 92, therefore no acid rain was detected. As a result, the pH of harvested rainwater still met the irrigation requirement after observing the standard deviation for each data set, except for Day 4. The water harvested in Day 4 is not suitable for irrigation purposes, as acid rain would affect the crops and soil health, which led to lower crop yield.

Table 4.2: Air Quality Index for Each Categories (Rahman et al., 2022)

Air Quality Index (API)	**Range of API**
Good	< 50
Moderate	51 to 100
Unhealthy	101 to 200
Extremely unhealthy	201 to 300
Hazardous	> 300

Moreover, electrical conductivity of rainwater in the storage tank was measured after rain hours. According to (Apera Instruments, 2018), the main factors that would affect the value of electrical conductivity are the temperature of the water, type of ions, and concentration of dissolved ions. Figure 4.14 shows the average electrical conductivity of rainwater at 27.5 ℃ in both design. According to Figure 4.14, the electrical conductivity of rainwater harvested using the system with a fine mesh filter was higher than the system with a first flush diverter. Therefore, it proved that the salinity of rainwater harvested with the fine mesh filter design was higher. The high salinity of rainwater is not suitable for irrigation purposes. This is because high salinity of rainwater would accumulate soluble salts in the root zone that are caused by various conditions such as crop, soil and climate. As a result, it would affect the crops production by stagnating the crops’growth and limiting the reproduction of the plants. However, based on the pH results shown in Figure 4.13, it proved that the pH of rainwater was unaffected by the different designs of the harvesting system. In addition, the automated harvesting system with a fine mesh filter was employed to filter suspended solid accumulated in the gutters during the dry period. Figure 4.15 illustrates the suspended solid that accumulated in the fine mesh filter design versus first flush diverter design.

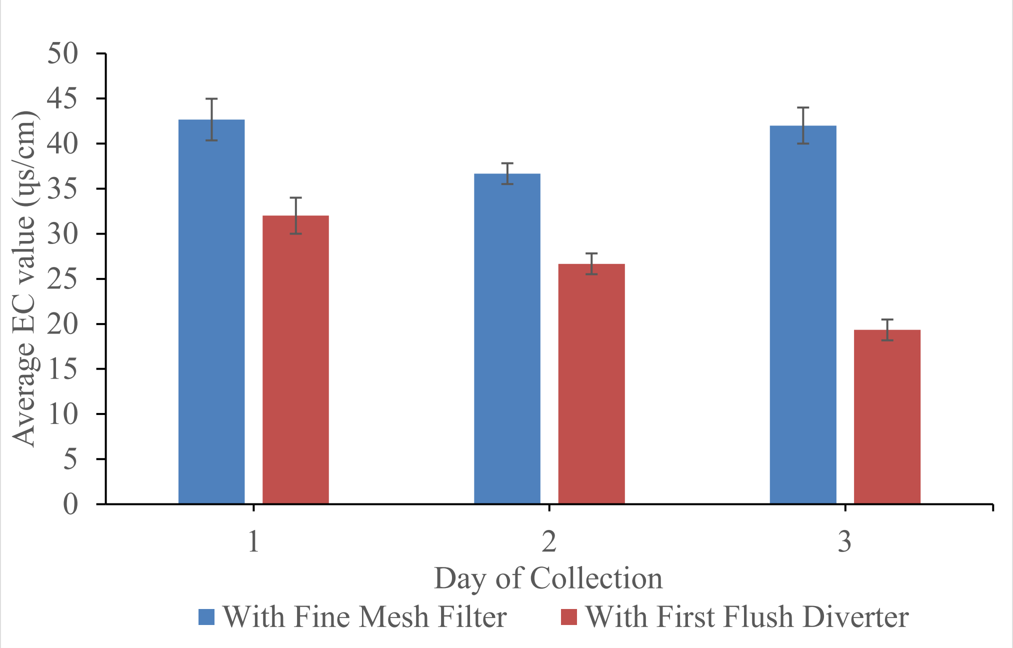


Figure 4.14: Average Electrical Conductivity of Rainwater at 27.5 °C in Both Designs

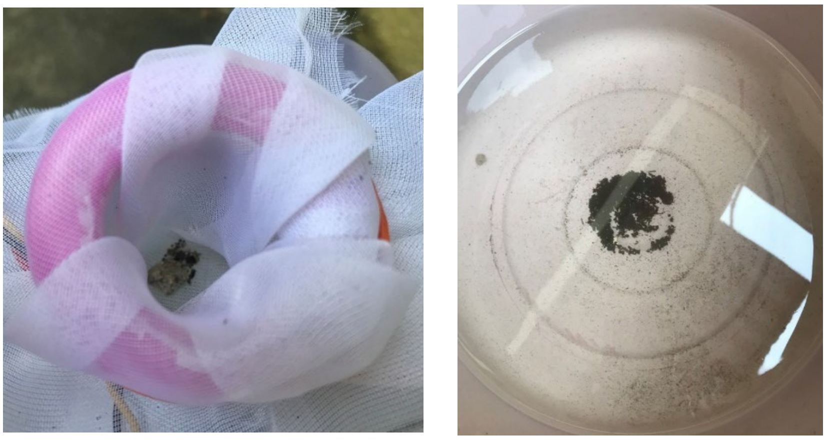


Figure 4.15: Suspended Solid that accumulated in the Fine Mesh Filter Design versus First Flush Diverter Design

Furthermore, by comparing the different design of the harvesting system, the volume of rainwater harvested can be determined as it decides the volume of rainwater that could be used for irrigation. In this experimental study, the total volume of rainwater harvested was compared between the two designs – with a first flush diverter and with a fine mesh filter. The volume of rainwater harvested was estimated based on the rainfall precipitation on each rainy day. Table 4.3 tabulated the total volume of rainwater harvested using two different designs. The total volume of rainwater harvested for 6 days using an automated RWHS with fine mesh filter and with first flush diverter was calculated to be 11.1 L and 8.1 L, respectively. According to Table 4.3, automated RWHS with a fine mesh filter could harvest a greater amount of rainwater than with a first flush diverter design. Thus, the automated RWHS with a fine mesh filter is superior to the first flush diverter design in terms of the volume of rainwater harvested, as it could harvest a greater amount of rainwater and reduce freshwater consumption for irrigation purposes.

Table 4.3: Total Volume of Rainwater Harvested by Using Two Different Designs

Day of collection	**Total Volume of Rainwater Harvested ($\frac{L}{day}$)**	
	Automated RWHS With Fine Mesh Filter	**Automated RWHS With First Flush Diverter**
Day 1	1.46	0.96
Day 2	1.44	0.94
Day 3	2.26	1.76
Day 4	1.41	0.91
Day 5	2.46	1.96
Day 6	2.06	1.56

4.2 Water and Cost Saving Potential

In this section, water and cost-saving potential of the automated RWHS was studied. The water-saving potential of automated RWHS is a critical factor used to optimise storage design and performance. As mentioned in Chapter 3.5, a literature review study on the chilli plant was conducted to calculate the water-saving potential of the automated RWHS. The total water needed for irrigating chilli plants is 1050 mm. Several assumptions were made in order to calculate the water needed to irrigate chilli plants. The crop area was assumed to be 2 $m^{2,}$ and the growing period of the chilli plant was assumed to be 90 days as according to the studies (N Anitha, 2018), the growing period of the chilli plant is between 80 to 90 days. The total water needed for irrigating the chilli plant was calculated to be 11.667 L/d. Note that the total number of collection days for automated RWHS with a first flush diverter and with a fine mesh filter was six, respectively. Therefore, the total water needed for irrigation in six days was 70 L.

Furthermore, Table 4.4 shows the results of water-saving potential for both designs. The automated RWHS with a first flush diverter harvested 8.1 L in 6 days, whereas the automated RWHS with a fine mesh filter harvested 11.1 L. As a result, the automated RWHS with a first flush diverter requires 61.9 L of freshwater, whereas automated RWHS with a fine mesh filter required 58.9 L. According to Table 4.5, the automated RWHS with a fine mesh filter shows a greater potential for water saving than the automated RWHS with a first flush diverter, with projected water saving potential of 13.1 % and 18.8 %, respectively. This is due to the fact that the first flush diverter diverted 0.5 L of rainfall precipitation in order to flush the contaminant leftover on the gutter during the dry season. Although the water saving potential of an automated RWHS with a fine mesh filter was higher, installing a first flush diverter is also advantageous as it does not require any filter medium to remove debris and other contaminants. On the other hand, an automated RWHS with a fine mesh filter could only filter out the suspended solids to maintain the quality of rainwater in the storage tank.

Table 4.4: Water Saving Potential for Both Designs

RWHS Design	**With First Flush Diverter**	**With Fine Mesh Filter**
Total volume of water harvested in 6 days (L/6 days)	8.1	11.1
Freshwater needed for irrigation (L/6 days)	61.9	58.9
Water saving potential (%)	13.1	18.8

In addition, the cost-saving potential of the automated RWHS was also calculated by including the annual rainfall precipitation in the study area in 2022 and water tariff in Malaysia. The water tariff in Malaysia for commercial use is RM 2.86/m^3 (Air Selangor Sdn. Bhd, 2022), while the annual rainfall precipitation in the year 2022 is 2960 mm. Before calculating the cost saving potential, the rooftop area was scaled up as the initial roof top area in this prototype is 0.186 m^2 which is significantly small for the calculation as it is a miniature automated RWHS. Therefore, the rooftop area was scaled up to 186 m^2 to calculate the cost-saving potential. According to (Heckman, 2021), the standard size of a gabled roof top for a greenhouse is 168.62 m^2, therefore the scaled-up rooftop area that was used for calculation in this experimental study is reasonable. Besides, based on the general guideline of a first flush diverter, 92.9 m^2 of roof area should divert 37.8 L of rainwater (Pushard D, 2022), therefore the volume of the first flush diverter was designed as 75.6 L.

The total volume of rainwater harvested by using an automated rainwater harvesting with a fine mesh filter was calculated to be 479,520 L/y. The average annual rainy days in this study area is 206 days. Therefore, the volume of rainwater removed by a first flush diverter was calculated to be 15,573.6 L. The total volume of rainwater harvested by using the automated RWHS with a first flush diverter was calculated to be 463,946.4 L/y. The amount of cost that could be saved by using an automated RWHS with a fine mesh filter is RM 1371.43 per year, whereas an automated RWHS with a first flush diverter could save RM 1326.89 per year. Based on water and cost saving potential, an automated RWHS with a fine mesh filter has greater potential in water and cost conservation as the harvested rainwater would pass through the catchment tank directly and stored in the storage tank for irrigation purposes if the rainwater quality meets the irrigation standard. The installation cost of a fine mesh filter is relatively cheaper than the installation of a first flush diverter.

4.3 Payback Period

The payback period of the automated RWHS was studied based on the scaled-up rooftop area (186 m^2). Several parameters were considered in order to calculate the harvesting system's payback period. The parameters include the capital cost of the system, the water tariff that is able to save and the operating costs of the harvesting system. Note that labour cost was not taken into consideration in the calculation. Table 4.5 and 4.6 show the cost of materials and quantity for a scaled-up automated RWHS equipped with a first flush diverter and with a fine mesh filter. The total capital cost for an automated RWHS with a first flush diverter and with a fine mesh filter was RM 2,140 and RM 1,810, respectively. The fine mesh filter that was employed in the automated RWHS was not included in the capital costs as it was a consumable required to change every month to maintain the rainwater harvesting efficiency constantly.

Table 4.5: Cost of Materials and Quantity for A Scaled up Automated RWHS Equipped with a First Flush Diverter

Materials	**Quantity**	**Price (RM)**
Arduino UNO Basic Starter Kit	1 set	80.00
AC to DC Adapter	1 pc	10.00
Relay Switch 5V to 12V	2 pcs	7.00
Solenoid Valve (4 in)	3 units	180.00
pH Module and pH Detector	1 set	80.00
PVC Pipe and Tools	4 m	50.00
SD Card Module	1 set	16.00
Stainless Steel Tank 20,000 L	2 units	1350.00
Float Switch	1 pc	7.00
Wire conduit	1 pc	10.00
First Flush Diverter	1 pc	350.00

Table 4.6: Cost of Materials and Quantity for A Scaled up Automated RWHS Equipped with Fine Mesh Filters

Materials	**Quantity**	**Price (RM)**
Arduino UNO Basic Starter Kit	1 set	80.00
AC to DC Adapter	1 pc	10.00
Relay Switch 5V to 12V	2 pcs	7.00
Solenoid Valve (4 in)	3 units	180.00
pH Module and pH Detector	1 set	80.00

PVC Pipe and Tools	4 m	70.00
SD Card Module	1 set	16.00
Stainless Steel Tank 20,000 L	2 units	1350.00
Float Switch	1 pc	7.00
Wire conduit	1 pc	10.00
Fine mesh filter	12 pcs	120.00

Besides, the annual operating cost was calculated based on the electricity consumption of the automated RWHS. The electricity tariff in Malaysia is RM 0.435/kWh under low voltage (1 to 200 kWh per month) (Tenaga Nasional Berhad, 2022). The annual electricity consumption for Arduino Uno was estimated as 236.52 kWh. Therefore, the annual operating cost is RM 102.89 using Equation 4.1. However, the operating cost for an automated RWHS with fine mesh filters was RM 222.89, which included the cost of replacing fine mesh filters annually. The operating costs for the automated RWHS with a first flush design was estimated as RM 514.45 whereas for fine mesh filter design was RM 1,114.45.

$$Operating\ cost\ \left(\frac{RM}{year}\right) = Electricity\ Tariff\ \left(\frac{RM}{kWh}\right) \times Electricity\ consumption\ \left(\frac{kWh}{year}\right) \tag{4.1}$$

Moreover, the total cost of the system was estimated by using Equation 4.2. The total cost for 5 years of the automated RWHS with first flush diverter and with fine mesh filter were RM 2,654.45 and RM 2924.45, respectively.

$$Total\ cost\ of\ system\ (RM) = Capital\ cost(RM) + Operating\ cost\ \left(\frac{RM}{5\ year}\right) \tag{4.2}$$

The payback period was estimated by using Equation 4.3. In addition, the water tariff saved in five years for the automated RWHS with a fine mesh filter and with a first flush diverter was RM 6,857.15 and RM 6,634.45, respectively. Therefore, the payback period for automated RWHS with a first flush diverter and with a fine mesh filter was 2.96 y and 3.37 y.

$$Payback\ Period\ (Year) = \frac{Water\ tariff\ saved\ in\ 5\ year\ (\frac{RM}{year})}{Total\ cost\ of\ system\ (RM)} \tag{4.3}$$

Table 4.7 shows the comparison of cost and payback period of different RWHS designs. Based on the calculated results, the payback period for an automated RWHS with a first flush diverter is shorter than the harvesting system with a fine mesh filter. This is because an automated RWHS with a fine mesh filter would require labour to change the fine mesh filter on a monthly basis. Therefore, it will lead to higher operating costs in the long run. The differences of payback period between the two designs were 0.4 year.

Table 4.7: Comparison of Cost and Payback Period of Different RWHS Designs

RWHS Design	**Automated RWHS with First Flush Diverter**	**Automated RWHS with Fine Mesh Filter**
Total capital cost (RM)	2,140.00	1,810.00
Total operating cost (RM/ 5 y)	514.45	1,114.45
Total cost of system (RM) – 5 y	2,654.45	2,924.45
Total water tariff saved (RM/5 y)	6,634.45	6,857.15
Payback Period (y)	2.96	3.37

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, the crucial integration of water quality control and monitoring of harvested rainwater is made possible in a sustainable and modern RWHS for urban agriculture, tailored to rainfall time series and water demand patterns of Klang Valley, Malaysia. More crucially, based on the analysis done, it becomes clear that the adoption of different designs and automation of RWHS has an impact on harvested rainwater quality and water saving potential. Based on the collected pH results, neither of these designs affects the pH reading; however, it affects the electrical conductivity of the harvested rainwater. In addition, acid rain was detected on one of the rainy days during the collection period, therefore, it was discharged by the automated RWHS. The electrical conductivity tested in both of the designs was in the range of 50 ɥs/cm. According to the irrigation water quality standard, the electrical conductivity of rainwater less than 250 ɥs/cm was considered good quality, therefore the harvested rainwater in the storage tank for both designs was usable.

Furthermore, the water and cost-saving potential of the automated RWHS was also assessed based on two different designs of the automated RWHS with a first flush diverter and a fine mesh filter. The cost-saving potential was estimated based on the scaled-up roof area, which is 186 m^2, and the water tariff in Malaysia. Based on the assessment, the automated RWHS with a fine mesh filter has a greater potential for water and cost conservation since it is capable of harvesting a greater amount of rainwater than the automated RWHS with a first flush diverter. However, the operating cost of the automated RWHS with a fine mesh filter is more costly due to constant replacement of the fine mesh filter which was required in order to preserve the high quality of rainwater. Within five years of operation, the payback period of automated RWHS with a first flush diverter is shorter than that of fine mesh design. Overall, the suitable minimal viable design of an automated RWHS for urban agriculture is the automated RWHS with a first flush diverter. Although it showed lesser potential for water and cost conservation than the fine mesh filter design, due to the presence of a first flush diverter, it could preserve a higher quality of rainwater for long-term usage. It could also reduce the maintenance cost of the entire system as the first flush diverter diverted the contaminants accumulated on the gutters. In conclusion, the findings highlight the potential of implementing an automated RWHS as a solution to issues linked to water scarcity, global urbanisation and climate change.

5.2 Recommendations for Future Work

Several recommendations are suggested in order to further enhance the automated RWHS for urban agriculture. Firstly, crop types should be one of the factors considered when deciding the sizing of an automated RWHS as different crop types have a certain amount of water needed for irrigation. Meanwhile, a soil moisture sensor can also be added to the automated RWHS to monitor the moisture of the soil and determine the amount of water needed for irrigation. Besides, future investigation is needed to evaluate and simulate the impacts of large scale RWHS on urban runoff drainage. A large scale automated RWHS is required to conduct multiple test at various location in order establish the water harvesting potential. In addition, an accurate and precise precipitation data is essential to further enhance the water harvesting potential of the automated RWHS. Regular maintenance of automated RWHS should be studied for large scale of RWHS in the future research as it ensure the quality of harvested water and also enhance the safety perception of farmers. Maintenance and labour costs should be include in the estimation of payback period of the system in order to estimate the return on investment of the harvesting system. Lastly, treatment system can be considered to add to the automated RWHS, however, it depends on the location in implementation of the automated RWHS as the industrial area may harvest rainwater that is slightly acidic. Therefore, in order to harvest a greater amount of rainfall, a treatment system could be implemented to treat the acid rain and then used for irrigation after treatment.

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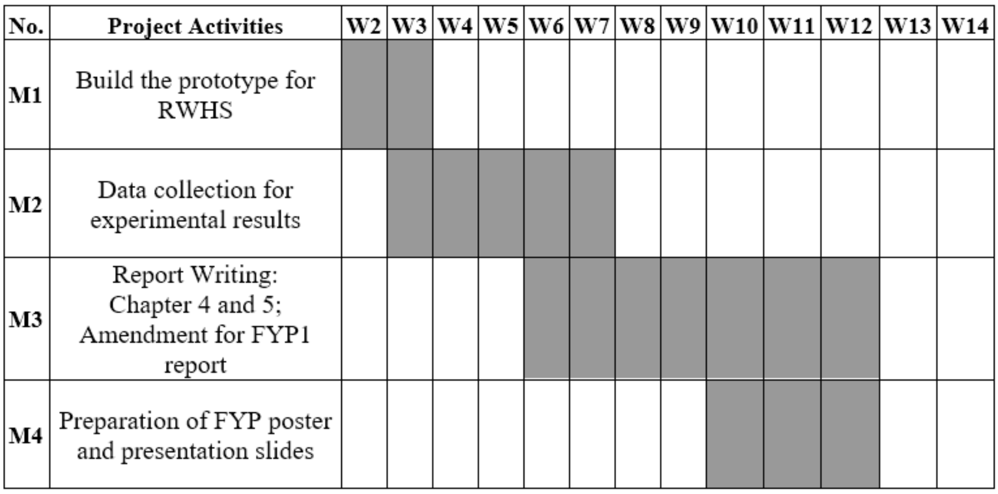
APPENDIX

Appendix A: Gantt Chart



No.	Project Activities	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
M1	Build the prototype for RWHS	■	■											
M2	Data collection for experimental results		■	■	■	■	■							
M3	Report Writing: Chapter 4 and 5; Amendment for FYP1 report					■	■	■	■	■	■	■		
M4	Preparation of FYP poster and presentation slides									■	■	■		

Figure A.1: Gantt Chart for FYP 2