PORTABLE LOW-COST WATER PURIFICATION SYSTEM FOR POPULATIONS IN DEVELOPING COUNTRIES AND EMERGENCY USE

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

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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 **“PORTABLE LOW-COST WATER PURIFICATION SYSTEM FOR POPULATIONS IN DEVELOPING COUNTRIES AND EMERGENCY USE”** was prepared by **KELVIN KEE MING ERN** and 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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ABSTRACT

Access to clean water is a major challenge, especially for developing countries facing water-related emergencies. Therefore, this study aims to propose a low-cost, portable water purification system that utilises agricultural waste as filter media. The filter media used were corn cobs, modified activated carbon (AC) and fruit peels (orange, dragon fruit, and banana peels) housed in a plastic drawer. This study evaluated the performance of the fruit peels in removing Fe^{3+} ions at different pH levels and concentrations. Additionally, this study also tested the antibacterial properties of AC coated with silver nanoparticles. Results showed that the best Fe^{3+} biosorption occurred when the initial concentration of Fe^{3+} was 25 mg/L at pH 7. The values of the maximum percentage removal of Fe^{3+} were 94.2879 %, 94.2358 % and 92.4361 % for banana, orange and dragon fruit peels, respectively. Furthermore, the ANOVA analysis results suggested that the type of fruit peels was insignificant as the biosorption capabilities of the proposed fruit peels were comparable under optimum conditions. Hence, orange, dragon fruit and banana peels are good candidates for Fe^{3+} removal. Besides, the AC coated with silver nanoparticles did inhibit the growth of E.coli, making it an excellent material for contaminant removal and water disinfection. Moreover, the proposed filtration system was able to reduce the Fe^{3+} concentration, conductivity, and turbidity values of the synthetic polluted water by 98.62 %, 40.00 %, and 81.73 %, respectively, indicating that agricultural wastes could potentially treat wastewater. However, further improvements are required to obtain safe water for human consumption as the treated water had yet to achieve potable standards, and its COD value increased by 247.06 %. The methods for improvement include optimising filter media depth and proper pre-treatments of biosorbents. It is also recommended to study the biosorption mechanism, kinetics, and reusability of the biosorbents to develop an economically feasible and environmentally sustainable water purification system.

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INTRODUCTION

1.1 General Introduction

Water has always been an essential resource to all living organisms as the cells require water to function properly. Drinking water helps to regulate body temperature, transport nutrients, maintain body fluid balance and so forth so that humans are able to live healthily. Aside from drinking, water has also played an essential role in this modern era as it can be used for recreation, agriculture, industries and domestic activities such as cooking, showering, washing clothes and toilets. According to the statistics from the National Water Services Commission (SPAN) in 2021, each Malaysian consumes about 201 litres of water daily. Hence, ensuring constant access to clean water is of the utmost importance in this day and age. (FOMCA, 2021)

However, according to the report published by the United Nations Children's Fund (UNICEF) in 2019, there are about 2.2 billion people in the globe do not have access to water that complies with the contemporary standards for safe water consumption. Most of them live in the rural areas of developing and least developed countries that lack basic and safely managed water services, which results in difficulties in obtaining clean water for daily activities and drinking. These people are subject to waterborne diseases such as diarrhoea, typhoid, cholera and parasitic diseases as they are constantly exposed to unclean and contaminated water. It is estimated that each year, 446 000 children die from diarrhoea, 129 000 people die from typhoid fever, and 95 000 people die from cholera. (CDC, 2022)

Besides, some water sources are polluted with harmful and toxic chemical substances from the nearby agricultural, industrial and illegal activities that do not follow the laws and regulations set by the local government. The common chemical pollutants include ammonia, phosphates, nitrates (from fertilizers), organic compounds and heavy metals such as mercury, cadmium, arsenic and lead. These chemical toxins are causative factors for neuroendocrine disruption, hepatic, renal and cardiovascular issues, cancer, as well as other serious health problems if ingested by humans at a certain amount. (Kumar, Borah and Devi, 2020).

On the other hand, cities with developed water purification and management system can also experience water supply issues, especially during flood disasters. During this event, the clean water would be contaminated with suspended solids and toxic chemicals due to changes and mixing of water streams. In addition, sometimes victims are forced to use flood water for domestic activities during the water shortage. As a result, the risk of spreading waterborne diseases increases during flood events. (See, Nayan and Rahaman, 2017)

In the situations mentioned above, it is crucial to have a sound water purification system to treat the poor-quality water to potable standards so that the people affected are able to drink and carry out domestic activities by using clean water without worrying about the negative impacts of consuming the contaminated water. Several portable water purification devices that utilise techniques such as boiling, ultraviolet (UV) light, pump filters, ozonation and chemical additives have been developed to solve the clean water supply issues and ease the emergency. These techniques usually require an electrical supply to work. However, some rural areas in the least developed countries and flood victims do not have electricity. Besides, some people from developing countries are unable to purchase and access these portable water purification units. (Venkatesha, Rao and Kedare, 2014)

Therefore, a low-cost yet effective portable water purification system that does not require electricity needs to be developed to solve the problems in the above circumstances. Research and studies have been done on biosorption to purify water. Biosorption is the physiochemical process that occurs on the surface of biological materials to bind and accumulate contaminants passively. Plant-based biomass, especially agricultural waste, is one of the biological materials that receive great attention from scientists due to its good adsorption capacity, low cost, and abundance on Earth. Agricultural wastes such as rice husks, fruit peels, and corncobs can be good candidates to be used as biosorbents to capture the harmful substances in the water as they are common even in rural areas. On top of that, chemical and physical modifications can also be easily done on these agricultural wastes to improve their biosorption efficiency and disinfection capability (Khatoon and Rai, 2016). Hence, due to the desirable characteristics and various advantages of using plant biomass as biosorbents, this project focuses on creating a portable water purification system that produces potable water safe for drinking and domestic use.

1.2 Importance of the Study

Various biological materials and plant biomass will be studied and used to make a portable water purification system that does not require electricity. The results of this study can bring significant impacts to mankind as the final product is able to produce water that achieves the minimum sanitary requirements for drinking.

The filter medium made from inexpensive and abundant plant biomass makes it feasible and easily accessible to the citizens in the least developed countries who do not have sufficient fresh water supply and safe water management systems. Besides, the product can also be used in emergency situations or after a natural disaster such as a flood, earthquake, or tsunami where clean water sources are temporarily unavailable. In short, the possible contribution of this study include:

- Create a low-cost and portable water purification system
- Provide a safe and clean water source to people from poor countries
- To achieve Sustainable Development Goal (SDG) 6: Clean Water and Sanitation
- Provide potable water for disaster relief and emergency use
- Understand the performance and biosorption capability of different biological materials and plant biomass under different pH values

1.3 Problem Statement

Currently, there are about a quarter of the human population who do not have clean water sources. These people are at a high risk of contracting water-borne diseases and chemical toxification as they do not have proper water purification systems. Although numerous studies have investigated the efficiency of filter media made from low-cost plant biomass, most papers only focus on removing a single contaminant. Besides, there are only a few scientific papers which reported the synthesis of polluted water that mimics real-life contaminated water in order to study the filtration efficiency of low-cost plant biomass. There are also limited publications that mention the combination of biomaterials to purify contaminated water. Apart from that, there is still a lack of studies on the disinfection of water by using modified plant biomass.

1.4 Aims and Objectives

The aim of this study is to propose a simple yet effective portable water purification system using low-cost plant biomass. The specific objectives are stated below:

- To propose a portable and convenient water filter body design.
- To evaluate the performance and adsorption capability of the proposed water purification system.
- To study the antibacterial activity exhibited by activated carbon impregnated with silver nanoparticles.
- To investigate the effects of pH values, initial concentrations, and type of fruit peels on the efficiency of Fe^{3+} removal.

1.5 Scope and Limitations of the Study

This study only focuses on the removal of common contaminants such as *E.coli*, iron, and solid particulate such as mud. It is known that each region has its main contaminants to be filtered from the water. Therefore, the proposed water purification system might not be applicable in every situation. Apart from that, there are only a few types of plant biomass involved in this study. Thus, there is a possibility of other biomaterials with better filtration capabilities to be discovered and used to replace the proposed filter media in the future. Besides, this study only investigates the effects of pH on the biosorption capacity of biomaterials, which is one of the most important paraments that affect the efficiency of pollutant uptake. However, the effects of other key parameters such as adsorbent dose, contact time, and temperature are not taken into account in this study.

1.6 Contribution of the Study

The contribution of this study includes developing a low-cost and portable water purification system, providing access to safe and clean water for those in underdeveloped countries and during emergencies, contributing to the achievement of SDG 6, and advancing the understanding of the performance and biosorption capability of different biological materials such as fruit peels.

1.7 Outline of the Report

The report consists of several chapters, which include literature review, methodology, results and discussion, as well as conclusions and recommendations.

This literature review includes deeper knowledge about the water scarcity faced by people in developing countries, where many of them suffer from overburdened water systems and limited access to clean water due to weak government and lack of proper infrastructure. Besides, natural disasters would contaminate water sources with various pollutants, making water unsafe to drink and causing outbreaks of diseases.

In addition, the literature review section also provides insights into the common composition of contaminated water sources, Malaysian drinking water standards, common types of low-cost biosorbents, biosorption mechanisms, treatments of biosorbents, and characterisation techniques. Furthermore, the effects of various parameters on biosorption capacity such as pH, initial concentration, and contact time are also included.

Subsequently, the methodology section covers the proposal for the portable water filter design, materials, and preparation of biosorbents. The experimental procedures and the analysis methods of the treated water samples are also explained in detail in this chapter.

Next, the section on results and discussion includes the evaluation of the performance of various fruit peels on Fe^{3+} removal based on the results of ICP-OES, FTIR, and Design Expert analysis. Moreover, the antimicrobial activity of AC coated with silver nanoparticles is also evaluated based on the interpretation of spread plate results. Then, the evaluation of the performance of the proposed portable water purification system is also addressed in this section by comparing the water analysis results between untreated and treated water.

Lastly, the chapter on conclusions and recommendations includes a summary of the research findings. This section also verifies the achievement of the objectives stated in this report. Apart from that, several suggestions are also provided to overcome the shortcomings of the research and enhance the overall research quality.

CHAPTER 2

LITERATURE REVIEW

Various scientific papers and publications have been reviewed to understand the pressing issues of clean water scarcity in least-developed countries and water quality concerns during natural disasters. Besides, the common contaminants in polluted water will be identified and the Malaysian drinking water standards will also be reviewed in this chapter to obtain ideas for the design of the portable water filtration system. Subsequently, the techniques of adsorbent synthesis using different low-cost plant biomasses as well as their performances have also been studied to determine the most suitable biomaterials for this study. Lastly, the effects of pH on the adsorption capability will be discussed in the last subsection of this chapter.

2.1 Clean Water Scarcity and Contamination of Water in Developing Countries and after Natural Disasters

2.1.1 Water Problems in Developing Countries

There are many developing countries in sub-Saharan Africa such as Nigeria, Angola, Cameroon and Chad are suffering from overburdened water systems and have limited access to clean water. Weak governments, poor long-term investment, mismanagement of resources, corruption, lack of urban infrastructure and environmental research are common in these countries. As a result, water-related problems such as poor sanitation, purification system and lack of utilities have caused the people in these countries to face clean water scarcity. (Tatlock, 2006)

Numerous public utilities that involve in the water management system experience a low-level equilibrium trap where the tariffs and resources allocated are unreasonably low. Even if tariffs are kept at a suitable level, a large proportion of resources are usually wasted as the utility given is a source of patronage from the highly inefficient governmental management and extractive procurement practices. Correspondingly, the water services are unreliable and the quality of water distributed to the rural areas is unsafe for daily consumption.

Therefore, the poor people are often forced to rely on expensive water sources from illegal water vendors or resort to dangerous alternatives such as polluted water. (Eberhard, 2019)

Besides, weak government enforcement and regulation have resulted in a high number of illegal disposals, unmonitored chemical usage as well as uncontrolled effluent discharges into the sub-Saharan African water sources. Appropriate adaptations and planning of water resources are limited because most of these countries do not have established water quality monitoring programmes.

Apart from that, there is also an unbalanced distribution of water treatment systems between the rural and urban regions in sub-Saharan African countries. For example, out of the 980 freshwater dams in sub-Saharan Africa, 589 of the dams are located in South Africa, which is a relatively more developed country. Meanwhile, there are only 2 dams in Tanzania which has a similar land mass and population as South Africa. Although Africa has abundant water resources, many sources have been heavily polluted and people in less developed countries do not have proper water treatment infrastructures (Fuller et al., 2022). Hence, the invention of an effective, low-cost water purification system is crucial to help provide clean water to these unprivileged people.

2.1.2 Contamination of Water after Natural Disasters

Natural disasters such as hurricanes, floods, earthquakes, tsunamis, and tornadoes are natural events that bring great loss and damage to mankind. 9 924 natural disasters took place globally between 1990 and 2019. Most of them (41.5 %) are floods, followed by storms (29.6 %). Earthquakes contribute to 8.2 % of the total number of global disasters during the above-mentioned period. (Vision of Humanity, 2020)

These catastrophes, particularly floods and tsunamis, can contaminate water supplies by introducing a huge amount of various pollutants such as nitrates, debris, pesticides, coliforms, sewage, heavy metals, and total dissolved solids into groundwater and surface water sources. However, the compositions of pollutants in the contaminated water via natural disasters are unpredictable as each region involves different human activities and geological settings. Therefore, studies often use the turbidity and conductivity values to quickly estimate the sanitation of water which the quality has been affected by natural disasters. Turbidity is the degree of cloudiness of a liquid while conductivity is a measurement of ionic content. Water with high turbidity and conductivity implies that the water consists of many chemical components and is heavily contaminated.

For example, the flood that happened in Johor, 2006 caused a high conductivity and total suspended solids in the water source, which signifies that the water is hazardous and requires proper purification methods so that it can be safe to consume. The Kasumigaura Lake in Myogihona of Japan which served as an important water resource to the nearby urban zone was found to have a high turbidity value due to the flood that occurred in 2006 (Yoshida et al., 2009). Besides, Typhoon Aere in 2004 which took place in Taiwan had caused the turbidity level in the Shihmen Reservoir to exceed 100 000 NTU. However, the turbidity of safe drinking water is advisable to be less than 5 NTU. Thus, the turbidity level in the Shihmen Reservoir significantly exceeded the threshold of the existing water treatment systems. Consequently, the southern Taoyuan district experienced a 19-day public water supply outage (Chou and Wu, 2010).

On the other hand, during a flood or tsunami, the clean drinking water sources are submerged by the engulfment of large water bodies that come into contact with many ground objects. Consequently, the disease-causing microorganisms are mixed in the water and can cause life-threatening health problems if the contaminated water is used or ingested by humans.

For instance, the 1998 flood disaster that occurred in Bangladesh caused a cholera outbreak. It was reported that the risk of flood victims contracting cholera increased by six folds as they had contacted with the contaminated water. Besides, since the victims were forced to gather in the flood relief centre, the crowding along with the compromised water management system and sanitary problems resulted in an ideal environment for the infectious pathogens to spread. In addition, the 2007 flood in Anhui province of China caused a surge in diarrheal disease by 317.5 %. There was also an increased number of cases of Hepatitis A virus infections during the 2007 Huai River flood in China (Lee, Perera, Glickman and Taing, 2020). According to the studies done by Mavrouli et al. (2021), polymicrobial respiratory infections are commonly diagnosed in near-drowned tsunami survivors. The common infectious microbial species include *Aeromonas*, *Streptococcus*, *E. coli*, and enteric gram-negative bacilli. Hence, numerous studies have shown that natural diseases can contaminate the water with various pathogens that can cause adverse health issues to humans or even death if it is consumed without any proper treatment. Table 2.1 below summarises some water-borne diseases and their respective illness-causing pathogens.

Table 2.1: Common Water-borne Diseases and Pathogens. (Reynolds, 2005)

Water-borne Disease	**Symptoms**	***Pathogen***
Escherichia Coli (*E.coli*) Infection	• Stomach pain, vomiting, diarrhoea, and bloody diarrhoea	Virulent *E.coli* strains
Dysentery	• Stomach pain, vomiting, fever, and diarrhoea	*Shigella*
Typhoid	• Stomach cramps, vomiting, nausea, fever and headache	*Salmonella typhi*
Cholera	• Stomach pain, vomiting and nausea	*Vibrio cholerae*
Hepatitis	• Stomach pain, fever, nausea, and fatigue	*Hepatitis virus*

2.2 Composition of Contaminated Water Sources

The composition of contaminated water sources varies and depends on their origin. For example, the polluted surface or groundwater from industrial sources usually contains a high concentration of synthetic compounds such as dyes, microplastics and fibres. Meanwhile, a high concentration of faecal content and nutrients are commonly found in the polluted water sources from rural areas.

According to Cisneros (2011), the common contaminants found in the surface or groundwater can be categorised into a few groups, which include: Acids (A), chlorine (Cl), disinfection by-products (DBP), endocrine disrupters (ED), emerging pollutants (EP), faecal pathogens (F), hydrocarbons (HC), heavy metals (HM), nutrients (N), nonmetal and anions (NMA), organic matter (OM), pesticides (P), personal care products (PCP), salinity (S) and toxins (T). The definitions of some groups are explained below.

DBPs are produced from the reaction between chemical treatment agents and other chemical compounds during the water disinfection process. Most of the DBPs are formed between the residual chlorine and natural organic matter such as humic and fulvic acids to produce harmful by-products. Besides, DBPs can also be formed from non-chlorinated disinfectants. For instance, the ozonation of water can produce formaldehyde and bromate ions, which are proven to be carcinogenic to human beings. On the other hand, endocrine disrupters (ED) are chemicals that interfere with the body’s hormone control system. These substances include polychlorinated biphenyls, phthalates and chlorpyrifos. (CDC, 2022)

Nutrient pollution is caused by excessive input of nutrients, especially the nitrogen, phosphorus and potassium-related chemical compounds present in commercial fertilisers. These pollutants can result in uncontrolled plant and algal growth as well as health effects including liver and kidney damage, skin rashes, respiratory problems or neurological issues (Adams, 2020). In addition, PCPs such as lipsticks, skin moisturisers and makeup kits are largely consumed by people nowadays. However, the water pollution caused by these products is difficult to be solved by using the conventional water treatment process due to their huge array of varieties. Apart from that, they can be life-threatening if they are accidentally ingested by humans in high amounts. (Khalid and Abdollahi, 2021).

In order to identify the most common contaminants in polluted water, Cisneros (2011) has concluded the main water polluting agents according to their respective origins in the following table.

Table 2.2: Sources of Contamination for Surface and Groundwater. (Cisneros, 2011)

Origin	Main Pollutants
Rural Areas	EP, F, HM, N, OM
Agricultural Areas	EP, F, N, OM, P, S
Industrial Areas	Variable, mostly synthetic compounds
Waste Disposal Sites	ED, F, HC, HM, NMA, OM, PCP, S, T
Urban Infrastructure Systems	DBP, ED, F, HC, N, OM, T, PCP, Sediments

Based on **Table 2.2**, it can be seen that OM is commonly found in most contaminated water sources. One of the most worrying organic pollutants is volatile organic compounds, such as phenol, dichloromethane, and benzene. Meanwhile, EP refers to a wide variety of complex organic compounds that are possible candidates to be monitored in the future for regulation. The examples of EPs include hormones, fragrances, surfactants, and flame retardants, which can be found in commercial products. These chemical compounds usually require complex and more costly analytical equipment to detect them. (Sauvé and Desrosiers, 2014)

Besides, **Table 2.2** shows that faecal pathogens are also usually present in polluted water. Hence, it must be ensured that a basic water treatment system must have the ability to disinfect the water or remove these harmful pathogens so that water-borne diseases can be prevented among the people who consume the treated water. Other the other hand, although heavy metals are only common in rural areas and waste disposal sites, their threats cannot be overlooked as they can be extremely toxic to the human body. These metallic elements can induce multiple organ damage even if they are present in a small quantity. According to the International Agency for Research on Cancer and the U.S. Environmental

Production Agency, heavy metals are also classified as carcinogens and the exposure has risen substantially over the past few decades due to the exponential increase of heavy metal use in technological and industrial applications (Tchounwou, Yedjou, Patlolla and Sutton, 2012). Therefore, these alerting chemical compounds are required to be taken into consideration when designing a water purification system.

Some examples of toxic metals, health concerns, and maximum exposure limit stated by the World Health Organisation (WHO) are mentioned in **Table 2.3** below:

Table 2.3: Common Metallic Contaminants and Their Respective Sources, Permissible Limits and Health Effects. (Bilal, Ihsanullah, Younas and Ul Hassan Shah, 2021)

Metal	**Sources**	**Maximum Permissible Limit (mg/L) by WHO**	**Health Effects**
Arsenic	Metal smelting, mining	0.010	Carcinogenic and dermatological, cardiorenal and gastrointestinal effects
Cadmium	Battery recycling plants, power plants, metal processing	0.003	Bones, kidney, heart, liver, and lung damage
Chromium	Textile and steel industry	0.050	Lung and kidney cancers, dermatitis
Copper	Metal smelting, mining	1.000	Abdominal pain, diarrhoea, lung cancer, liver toxicity

Mercury	Pharmaceutical products, pesticides, thermometers, paints and paper industries, oil refining, batteries, rubber processing,	0.010	Degradation of kidneys, lungs, digestive, nervous, and immune systems
Lead	Smelting, mining, and automobile industries	0.010	Affect the central nervous systems, livers, and kidneys
Zinc	Cosmetics, pharmaceutical products, insecticides, pigment, galvanising	3.000	Anaemia, abdominal pain, vomiting, and plant toxicity
Iron	Fertilisers, mining, pipe corrosion, steel industry, and textile manufacturing	0.300	Diarrhoea, vomiting blood, seizures, liver failure, and metabolic acidosis

2.3 Drinking Water Quality Standards in Malaysia

The national standard for drinking water has been set up by the Engineering Services Division, Ministry of Health Malaysia (MOH) to ensure that the drinking water distributed to the citizens is clear, safe, and does not have objectionable colour, taste, and odour. A list of parameters which include the presence of chemical substances, microbiological activity, physical properties of water and other emerging pollutants are taken into consideration during the preparation of the national standard for drinking water quality.

The objective of this guideline is to set maximum permissible limits to the constituents which may be dangerous to humans or objectionable to the physical senses of the users. A few parameters and their maximum acceptable value set by MOH are presented in **Table 2.4** below.

Table 2.4: Malaysian Drinking Water Quality Standards. (MOH, 2004)

Parameters	**Maximum Permissible Limit (mg/L, unless otherwise stated)**
Total coliform and *E. coli*	Absent in 100 mL
Viruses, helminths, and protozoa	Absent in 100 mL
Total dissolved solids (TDS)	1000
Chemical Oxygen Demand (COD)	10
Chloride	250
Ammonia	1.5
Iron	0.3
Magnesium	150
Sulphate	250
Sodium	200
Arsenic	0.010
Cadmium	0.003
Mercury	0.001
Lead	0.010
Manganese	0.100
Silver	0.050

Besides, the recommended turbidity value and colour are 5 NTU and 15 TCU respectively. The pH of the drinking water must fall within the range of 6.5 to 9.0 to fulfil the drinking water requirement set by MOH (2004).

2.4 Biosorbents and Biosorption Mechanisms

Adsorption is a mass transfer process that involves the accumulation of chemical substances at the interface of a two-phase system. The adsorption of substances onto biomaterials is called biosorption. Besides, the adsorbents synthesised from biomaterials are called biosorbents. Biomaterials are generally great biosorbents as their surfaces consist of different functional groups. The examples of functional groups include amino, hydroxyl, carboxyl, and carbonyl groups, where most of them are negatively charged. These functional groups naturally attract cationic contaminants to be adsorbed onto their surfaces. Besides, the presence of numerous cavities and pores on the biomaterial surface can also help to trap and adsorb unwanted substances (Ambaye et al., 2020). Hence, biomaterials especially low-cost plant-based biomass are suitable to be converted into biosorbents so that green and economical alternatives used to purify contaminated water can be obtained.

There are several possible biosorption mechanisms of contaminants onto biosorbents. For example, metallic ions can be adsorbed onto the biomaterial surface through ion exchange, surface sorption, precipitation, complexation, and electrostatic interactions. Surface sorption occurs when the metal ions diffuse into the pores and adhere to the surface via chemical bonding (Kumar et al., 2017). For precipitation, the metal ions react with the surface chemicals and form insoluble substances on the biosorbents. On the other hand, complexation involves the interaction between functional groups and heavy metals to produce metal ligands, whereas electrostatic interactions involve the attraction between positively charged metallic ions and negatively charged substances. (Mukherjee, Zimmerman and Harris, 2011)

The adsorption mechanisms for organic substances are different from the mechanisms involved in the adsorption of metals. Common adsorption mechanisms for organic contaminants include hydrophobic interaction, pore filling, electrostatic interaction, partitioning and hydrogen bonding. The hydrophobic interaction is the observed tendency of hydrophobic substances to cluster together in an aqueous solution and expose the less hydrophobic/ hydrophilic parts to the outer environment. Pore filling is a process where the organic pollutants are stuck with the pores on the surface of biosorbents. Meanwhile, partitioning takes place when there is a presence of a noncarbonised portion in the biosorbents. The organic pollutants diffuse into the pores and interact with this portion and eventually bind to the inner surface. (Ahmad et al., 2014)

The common mechanisms applied to remove organic and inorganic pollutants in the water are summarised and illustrated in **Figure 2.1** below, where biochar is used as an example for biosorbents.

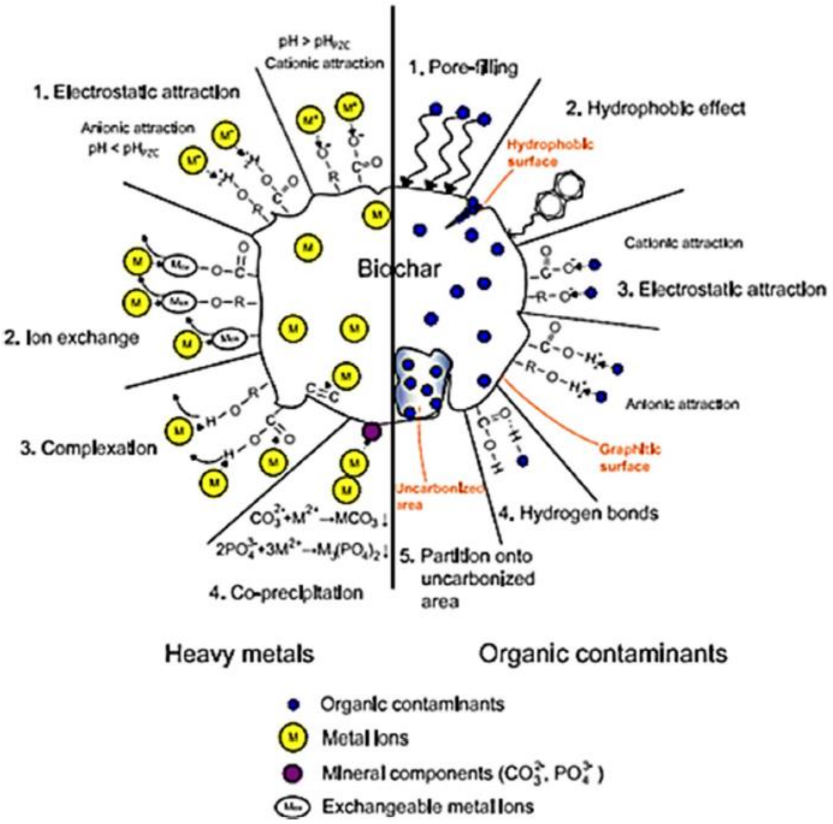


Figure 2.1: Different Biosorption Mechanisms for Organic and Inorganic Pollutants Removal. (Ambaye et al., 2020)

2.5 Treatments and Modifications of Biosorbents

Biomaterials are often subjected to some treatments and modifications before being used as biosorbents in order to improve their biosorption capabilities. Each biomaterial has its own suitable treatment method and conditions to achieve a successful activation. Besides, a few modifications can also be done to the biosorbents to further enhance their efficiencies and functions. The following subsections discuss several common treatments of biomaterials to obtain effective biosorbents.

2.5.1 Physical Treatment

This treatment method involves washing, drying and size reduction. Physical treatments have the lowest synthesis costs and do not go through a series of processing and activations. Some of the biosorbents only undergo physical treatments to obtain desirable biosorption capacities as these bio-substances are naturally good adsorption materials. Most of the plant biomass and waste can be prepared by washing them thoroughly to remove impurities and drying them at temperatures ranging from 40 to 120 °C for 2 hours to 7 days. Lastly, they are crushed or ground to the desired size to improve their surface-area-to-volume ratio and adsorption efficiency.

Each biosorbent has its own optimal drying temperature and period to achieve the targeted biosorption capacity. For instance, the *Pinus halepensis* sawdust was dried at 100 °C for 2 days (Semerjian, 2018). Fish wastes were washed and dried at 80 °C for 1 day to become a biosorbent for cadmium ions (Jaafar et al., 2021). Similarly, an effective biosorbent developed from potato peels can be obtained by washing them and drying them at 50 °C for 7 days (Guechi and Hamdaoui, 2015).

2.5.2 Chemical Treatment

This treatment is used to activate the pore sizes on the surface of biosorbents. The activated pores will exhibit an improved electrostatic interaction with heavy metallic ions. Hence, the biosorbents will have a stronger affinity to attract and adsorb cationic pollutants. Although some of the biosorbents that undergo physical treatments can have satisfactory performance, their biosorption capacities can be further improved by applying chemical modifications as their surface charge and distribution of functional groups can be altered to significantly increase their adsorption abilities. (Ma et al., 2014)

The chemical treatment of biosorbents usually involves the usage of acids and alkalis such as hydrochloric acid, sulphuric acid, sodium hydride and calcium hydroxide to activate the adsorption sites of the biosorbents. Kumar and Chauhan (2019) treated the hyacinth roots using 0.5 N hydrochloric acid and 0.5 N sodium hydroxide for 3 hours and dried them at 100 °C for a day. Besides, the biosorbent developed from green tea waste was immersed in 0.05 M calcium hydroxide solution for 10 hours to chemically improve its biosorption capacity (Yang et al., 2016). A few extensive studies from researchers such as Moyo, Pakade and Modise (2017) and Herrera-Barros et al. (2020) have also proved that chemically modified biosorbents in an aqueous environment perform better than unmodified biosorbents.

2.5.3 Heat Treatment

This treatment method uses a high amount of energy to activate and improve the surface area of the biosorbents. The improved surface area gives a higher availability of biosorption sites for the uptake of contaminants. Usually, the heat treatment is performed on the crushed or ground biomass by subjecting them to a temperature of 300 to 900 °C for 2 to 4 hours under a nitrogen atmosphere. A study showed that the biosorbents synthesized from walnut nuts were pyrolyzed at 600 °C under a pure nitrogen atmosphere (Zbair, Ait Ahsaine, Anfar and Slassi, 2019). Besides, Bhatnagar, Minocha and Sillanpää (2010) treated lemon peels at 500 °C to thermally activate them. Similarly, another study activated the corn cobs by burning them at 500 °C. (Adie, Lukman, Sani and Yahaya, 2013)

2.5.4 Impregnation

This method involves the loading of a porous biomaterial with a metal component under dry or wet conditions. Dry impregnation is done by adding the desired amount of metal solids to the biomaterials. Meanwhile, wet impregnation involves the immersion of biomaterials in an excess aqueous solution containing the targeted metal components to distribute them evenly on the internal surface of the biomaterials. The addition of foreign metal components can help to improve the biosorption capacity for certain contaminants and also disinfect the water. The impregnated biosorbent is reported ta have better stability and a promising regeneration capability.

A study conducted by Shah et al. (2015) showed that the efficiency of methylene blue removal using activated carbon could be improved by 95 % after being treated with wet iron impregnation. Besides, studies also found that the activated carbon impregnated with zinc oxide can help to adsorb more organic contaminants and degrade them via catalysis. (Taha, Ben Aissa and Da’na, 2020)

On top of that, the impregnation of nanoparticles on biosorbents has also been studied by various researchers due to their huge surface-to-volume ratio, which allows them to be more reactive and efficient than bulk materials. For instance, the adsorption capacity of nickel using orange peels impregnated with titanium dioxide nanoparticles increased by two-fold compared to the untreated orange peels (Herrera-Barros et al., 2022). Besides, a magnetic nanocomposite made of chitosan and zerovalent iron was coated on sugarcane biochar, which helped to improve its carbamazepine and aspirin uptakes. (Siddiqui et al., 2023)

Furthermore, the impregnation of silver nanoparticles on porous materials has recently received more and more attention to disinfect water. The studied materials include activated carbon, alginate beads, polymeric microspheres, polyurethane, and resin beads. Nevertheless, activated carbon is one of the most preferred media. It is widely used in household filtration systems due to its large surface area and high efficiency in removing organic and inorganic pollutants. The activated carbon can undergo plasma treatment prior to impregnation to reduce the requirement of silver loading. Over the past decades, studies reported that the activated carbon impregnated with silver nanoparticles showed antimicrobial activity against *S. aureus*, *P. aeruginosa*, and *E. coli*. (Biswas & Bandyopadhyaya, 2016)

2.6 Current Studies on Pollutant Removal Using Low-Cost Biosorbents

Various researchers have used different biomaterials and agricultural wastes as biosorbents for contaminant removal. **Table 2.5** below summarises some of the results from the studies, which include the types of biosorbents, target contaminants and biosorption efficiency.

Table 2.5: Examples of Biosorbents Studied and Their Performances.

Plant Biomasses	Description	Literature Sources
Rice Husk	Rice husk was found to be an effective biosorbent for heavy metal ions, synthetic dyes and organic contaminants such as phenol. The treated rice husk could adsorb methylene blue at 312 mg/g, which is an organic chloride salt that serves as a dangerous pollutant. Besides, the biochar developed from rice husk could also remove cadmium ions with a biosorption capacity of 93.5 mg/g from the water.	(Bishnoi, et al., 2004), (Ajmal, et al., 2003), (Kannan and Sundaram, 2001)
Plant Seeds	Several plant seeds obtained from moringa, jackfruit, nelli, mangrove apple and java plum have been studied and proved to be effective in removing harmful ions in water such as magnesium, iron, cadmium, calcium, chloride and fluoride ions. Besides, they can also remove the colours, odours, and total dissolved solids in water.	(Arasaretnam and Keerthanan, 2018)

Sugarcane Bagasse	Sugarcane bagasse contains a huge variety of functional groups. A biosorbent synthesised from sugarcane dust has been used to remove methylene blue, rhodamine B, and crystal violet from an aqueous. In addition, sugarcane bagasse was found to be capable of removing 94-95% of Basic Blue 9 dyes from industrial effluents.	(Khattri and Singh, 1999), (Zhang, et al., 2013)
Corn Cobs	Biosorbents made from corn cobs are used to remove total dissolved solids and reduce turbidity from the water. This agricultural waste is abundant in some rural areas, which is a good candidate to be used as filter media. The powdered corn cob has a biosorption capacity of 4.33 mg/g for arsenic (III) ions. Besides, activated corn cobs can remove 66 % of ammonia nitrogen and 28 % of chloride ions from polluted water.	(Adie, Lukman, Sani and Yahaya, 2013)
Fruit Peels	Banana peels, lychee peels and orange peels have adsorption capacities of 98.4 mg/g, 230.5 mg/g and 170.3 mg/g respectively for the removal of cadmium ions. Their performances are significantly better than rice husks, egg shells, and potato peels. Besides, banana peels also have a biosorption capacity of 87.5 mg/g for lead ions removal. On the other hand, dragon fruit peels proved to have biosorption capacities of 36.5 mg/g and 15.5 mg/g for cadmium (II) and manganese (II) ions respectively.	(Bilal, Ihsanullah, Younas and Ul Hassan Shah, 2021), (Tanasal, Nafie and Taba, 2015)

Activated Carbon	Activated carbon is synthesised by pyrolysis of plant biomass. It can be any carbonaceous material such as coal, wood, coconut shells and corn cobs. The activated carbon, which is often used as the filter medium can have a filtration efficiency of 99 % for the removal of harmful substances such as volatile organic compounds, total suspended solids, chloramines and heavy metals. Besides, since activated carbon contains numerous pores, it can be coated with silver nanoparticles to disinfect the water filtered. The activated carbon with 2.5mg/g of silver nanoparticles can reduce 99.7 % of bacteria after 3 mins of contact time.	(El-Aassar, Said, Abdel-Gawad and Shawky, 2013)

Table 2.5 only involves some of the biosorbents developed from common plant biomasses. In fact, many researchers have utilised a huge array of plant-based biomaterials such as corn straw, celery, sugar beet tailing, oak wood, leaves, tea, and sawdust to treat various inorganic pollutants which include lead, copper, zinc, fluoride, phosphate and even uranium. Meanwhile, biomaterials such as bamboo, kenaf fibre, peanut straw, pine needle biochar, and Quercus wood have also been studied and converted to biosorbents to remove hazardous organic contaminants such as phenol, naphthalene, atrazine, bisphenol, and synthetic dyes (Ambaye et al., 2020). Hence, the efforts contributed by researchers from around the world have shown that plant biomass, especially agricultural waste has great potential to become an effective alternative for water purification media.

2.7 Key Parameters Affecting the Biosorption Capacity

2.7.1 pH

Various studies show that the pH value of the aqueous can impact the adsorption of contaminants onto biosorbents. It is reported that the changes in pH values would affect the surface chemistry and charges around the functional groups of the adsorbent. Besides, the ionisation of the metal ions and adsorbate speciation can also be altered by the pH of the aqueous solution. (Ambaye et al., 2020)

According to the study done by Lu et al. (2012), as the pH of the aqueous solution increases, deprotonation takes place at the functional groups of the biochar, which results in an increased uptake of the cationic metals. Nevertheless, as the pH decreases, the electrostatic repulsion forces between heavy metal ions and protons increase. In addition, the increasing number of H^+ ions would compete with the cationic metal ions for the limited adsorption sites on the biochar surface. As a result, the biosorption capacity of the biochar for metal ions decreases.

Since the types of functional groups and surface chemistry for each biosorbent are different, the surface charge of the biosorbent at various pH can be determined by the point of zero charge (PZC) analysis to predict its biosorption capacity when exposed to aqueous solutions of different pH values. For instance, the PZC for sugarcane bagasse, tomato waste and olive stone are 5.7, 8.9 and 4.2 respectively. If the pH value is below the PZC, the surface of the biosorbent becomes positively charged due to the increased number of protons donated from the acidic aqueous solution. Hence, the biosorbent surface attracts anionic substances and repels cationic substances. On the other hand, if the pH value is higher than the PZC, the number of hydroxide groups present in the aqueous solution increases (Bilal, Ihsanullah, Younas and Ul Hassan Shah, 2021). Hence, the surface of the biosorbent attracts cationic substances and repels anionic substances.

Generally, a higher biosorption capacity of cationic pollutants (such as heavy metals) can be observed at higher pH values, whereas anionic pollutants exhibit a higher biosorption capacity at lower pH values. For example, a study found that the uptake capacity of cadmium (II) ions by using radish peels increases as the pH increases from 2 to 9 (Ashraf, Rehman, Alias and Yusoff, 2013). Besides, the adsorption of organic dyes on the biochar made from food waste is enhanced under alkaline pH due to a high interaction between the positively charged organic dyes and the negatively charged biochar surface.

Chen et al. (2011) reported that the biosorption capacities of activated corn straw for zinc and copper ions increase as the pH increases from 2 to 5. However, the adsorption performance drops at pH values above 5 due to the formation of insoluble metal hydroxides. Besides, another study observed that the optimum pH value for nickel (II), cadmium (II) and lead (II) biosorption using a Chesapeake blue crab biomass is 6 instead of alkaline pH values. Hence, the chemical properties of the contaminants under different pH values can also affect the number of pollutant uptakes. In short, the biosorption capacity of a biosorbent depends greatly on the pH value of the aqueous solution.

2.7.2 Initial Concentration of the Target Contaminant

The percentage removal of the target contaminant is directly influenced by its initial concentration. Generally, as the concentration of the target contaminant increases, the biosorption efficiency increases due to the increase in the frequency of collisions between contaminants and binding sites, which improves the likelihood of pollutants being adsorbed onto the biosorbent. However, there will be a maximum biosorption efficiency for each biosorbent, which will be achieved once the contaminants have fully occupied all the vacant binding sites. (Bilal, Ihsanullah, Younas and Ul Hassan Shah, 2021)

2.7.3 Temperature

The changes in temperature can significantly affect the biosorption capacity and the physiochemical characteristics of the biosorbents. The biosorption process can be categorised into an exothermic or endothermic process. The biosorption rate increases with increasing temperature when the process is endothermic, whereas the biosorption rate decreases with increasing temperature in an exothermic process.

For instance, the maximum biosorption capacity of Ni(II) using modified *Aloe barbadensis* miller leaf powder was 13.15 mg/g at 293 K. However, the value decreased linearly with the increment of temperature due to the weakening of hydrogen bonding (exothermic process) and Van der Waals interactions at higher temperatures.

Meanwhile, the biosorption of Cr(VI) ions using *Moringa* pods increased at elevated temperatures, which showed that the main biosorption mechanism was an endothermic reaction. Besides, it was also reported that the increase in temperature caused a reduction in mass transfer resistance of the boundary layer, which allowed the contaminants to be more readily adsorbed onto the binding sites. Therefore, the selection of suitable temperatures for biosorption is crucial as it determines the practicability of the prepared biosorbents in a real water treatment system by considering the energy requirement. (Bilal, Ihsanullah, Younas and Ul Hassan Shah, 2021)

2.7.4 Biosorbent Dosage

In general, the increase in biosorbent dosage will increase the contaminant uptake as the number of vacant binding sites is higher. Several studies reported that the increment in Co(II) and Cr(VI) biosorption efficiencies was observed when the biosorbent dosage was higher until the biosorption equilibrium was achieved. Afterwards, any further increase in the biosorbent dosage would not effectively enhance the pollutant uptake as the ratio of the remaining amount of pollutants to the number of available biosorption sites is too low, which decreases the probability of biosorption. (Bilal, Ihsanullah, Younas and Ul Hassan Shah, 2021)

2.7.5 Presence of Competing Contaminants

In practice, wastewater often contains various and co-existing contaminants, which can affect the biosorption efficiency. This is because a limited number of active sites are present in a fixed amount of biosorbent dosage, which causes different contaminants to compete for the limited binding sites, especially when their concentrations are high. Therefore, the development and design of a biosorption system must consider a multi-component basis to assess its performance in real-life applications. However, this parameter is rarely addressed and studied by researchers. For example, a study done by Cay et al. (2004) focused on the removal of Cd(II) and Cu(II) by using modified tea waste.

2.7.6 Contact Time

Normally, the percentage removal of contaminants increases as the contact time increases until an equilibrium is reached. This is because the increase in contact time causes the number of effective collisions between the contaminants and active sites to increase. Consequently, a higher amount of contaminants can be adsorbed onto the surface of biosorbents. The values of biosorption equilibrium differ for each biosorbent. For instance, a study found that the time taken for cadmium and lead ions to achieve biosorption equilibrium was 4 hours and 1 hour, respectively. (Lee & Choi, 2018)

2.8 Characterization of Biosorbents

The characteristics of the biosorbents can be assessed by utilising various techniques. The commonly used instruments include Brunauer-Emmett-Teller (BET) analyser, X-ray diffraction (XRD) analyser, energy-dispersive X-ray spectroscopy (EDS), inductively coupled plasma optical emission spectroscopy (ICP-OES), scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR).

A BET analyser is used for the determination of the surface area and pore size distribution of a biosorbent. XRD analyser is employed to investigate the structural crystallinity of a material. Meanwhile, EDS is utilised to illustrate the elemental analysis and chemical characterization of different biosorbents.

The ICP-OES is used to measure the concentrations of elements in an aqueous solution, whereas the SEM is used to study the elemental information and morphology of the biosorbents. SEM can also show the structures and surface characterizations of the biosorbents. Additionally, FTIR is used to determine the presence of extensive functional groups which are involved in the biosorption mechanism. FTIR can also show the changes in surface properties and functional groups of the biosorbents after filtration.

2.9 Summary

After the completion of the literature review, it is aware that there is a need for a portable water purification system made from low-cost biomaterials to help people in the least-developed countries to have access to clean and safe water. In addition, this portable water purification system can also be used for emergency and disaster relief situations, especially when the water source is contaminated with high amounts of solid particulate. On the other hand, the most common and hazardous contaminants such as faecal pathogens and metals have been identified. In this study, the removal of iron and *E.coli* will be focused on and addressed. The AC will be impregnated with silver nanoparticles in order to test its antibacterial property on *E.coli*. Besides, some examples of biosorbents have also been reviewed to determine the most suitable biosorbents to be used for this study. Hence, corn cobs and peels from fruits such as bananas, oranges and dragon fruits have been chosen as the biosorbents to treat contaminated water to drinking standards due to their satisfactory biosorption performances and high accessibility in the market. Apart from that, since the pH value and initial concentration of contaminants can affect the biosorption capacities of biosorbents, the performance of the fruit peels in iron removal will be evaluated under different pH levels and initial concentrations to study their effects. Lastly, this study will use powerful analytical instruments such as SEM and FTIR for biosorbent characterisation.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Portable Water Filter Design

The goal is to design a simple, portable yet effective water purification system. Since various plant-based biosorbents are used and each of them has its own degradation rate, the portable water filter must include a trayed system to replace the degraded biomass without refilling the whole filter medium. Hence, a common daily object, multi-tier mini drawer, can be used as the water filter body with some modifications.

Figure 3.1: A 6-tier Plastic Mini Drawer.

First, the top cover of the mini drawer is removable. It can serve as the polluted water inlet. Small holes can be drilled beneath each layer of drawers to ensure that the filtrate can flow through the filter medium. Besides, teabags are cut and placed on the bottom of each drawer to prevent the filter media from leaking into the subsequent compartment. The portable filter design is presented in the drawing below:

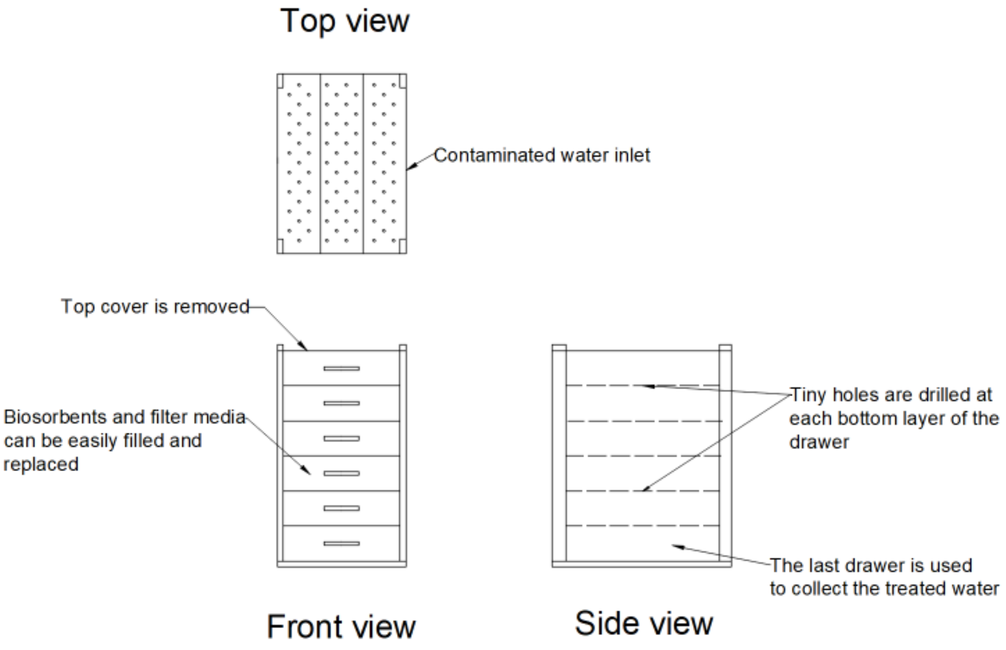


Figure 3.2: The Proposed Portable Water Filter Design.

The bottom layer of the last drawer is not drilled as it can be utilised to store the treated water. The number of layers of the drawer depends on the number of biosorbents or filter media used. Besides, the plastic drawer used is transparent so that the flow of water can be observed. If the required water output is higher than the volume of the last drawer, holes can be drilled beneath it and a bucket can be placed below the filter body to collect the purified water.

3.2 Materials

Corn cobs, banana peels, orange peels, dragon fruit peels, activated carbon (AC) and fine sand with sizes of 0.6 – 1.2 mm were obtained from the market. The chemicals including hydrochloric acid (HCl), sodium hydroxide (NaOH), nitric acid (HNO_3), silver nitrate solution ($AgNO_3$), and glucose powder were prepared for the experiment. Besides, distilled water and deionised (DI) water were also prepared and obtained in the laboratory.

The chemicals and materials used for the preparation of synthetic polluted river water and water quality analysis are mentioned in detail under **Section 3.5** and **Section 3.7** respectively.

3.3 Preparation of Biosorbents

The collected corn cobs and fruit peels underwent a few preparation steps to convert them to biosorbents.

3.3.1 Corn Cob

The corn cobs were washed thoroughly using tap water, followed by distilled water. They were then dried in an oven at 80 °C until a constant weight was obtained. Next, they were cut into big and small pieces accordingly using a knife.

3.3.2 Fruit Peels

The peels from bananas, oranges and dragon fruits were washed thoroughly using tap water, followed by distilled water. Then, these peels were dried in an oven at 80 °C until a constant weight was obtained. The dried peels were then ground in a grinder to reduce their size and sieved to a particle size of 0.149 mm (100 mesh). Lastly, they were kept in a desiccator for later use. (Chen, Wang, Zhao and Huang, 2018)

3.4 Coating of Silver Nanoparticles on Activated Carbon

The AC was treated with a series of hot concentrated (69 %) HNO_3, hot distilled water, hot 10 M sodium hydroxide solution and followed by hot distilled water again. The steps above were repeated three times. Personal protective equipment (PPE) was worn properly during the experiment. Besides, the steps above were carried out in a fume hood to avoid the inhalation of toxic gases such as HNO_3. Then, the treated AC was dried in an oven at 110 °C for 3 hours.

On the other hand, 1.70 g of glucose was dissolved in 50 mL of DI water in a conical flask wrapped with aluminium foil. 1 mL of 0.1 M NaOH was added to the conical flask to act as a catalyst. Next, 0.425 g of silver nitrate was dissolved in 200 mL of DI water. The silver nitrate solution was then added drop-wise into the conical flask at a rate of 2.5 mL min^{-1}. The reaction was carried out at 70 °C with a stirring speed of 150 rpm. As a result, a brownish colloidal solution of silver nanoparticles was obtained. The experimental setup is shown in **Figure 3.3** below:

Figure 3.3: Experimental Setup to Produce Silver Nanoparticles.

The treated AC was soaked in the silver nanoparticle solution under vigorous stirring at room temperature for 12 hours. The AC coated with silver was then dried in an oven at 110 °C for 2 hours to obtain the AC which was fully coated with silver. (El-Aassar, Said, Abdel-Gawad and Shawky, 2013)

3.5 Preparation of Synthetic Contaminated Water

The following subsections describe the contents and amounts of chemicals used to produce synthetic contaminated water for experimental use.

3.5.1 Preparation of Iron (III) Chloride Solutions for Batch Experiments

To test the adsorption ability of fruit peels for Fe^{3+} ions under different conditions, the $FeCl_3$ solutions with varying pH values and concentrations were prepared. 1 litre of 1000 ppm Fe^{3+} solution (2904.73 mg/L $FeCl_3$) was prepared to be diluted. 0.1 M of HCl and 0.1 M of NaOH were used to adjust the pH of the solutions. Table 3.1 below summarises the details of the $FeCl_3$ solutions prepared for the batch experiments :

Table 3.1: Details of the Prepared $FeCl_3$ Solutions.

pH	**Concentration of Fe^{3+}**		
	5 mg/L	**15 mg/L**	**25 mg/L**
3	pH 3, 5 mg/L	pH 3, 15 mg/L	pH 3, 25 mg/L
7	pH 7, 5 mg/L	pH 7, 15 mg/L	pH 7, 25 mg/L
11	pH 11, 5 mg/L	pH 11, 15 mg/L	pH 11, 25 mg/L

Three levels of pH values and three levels of Fe^{3+} concentrations were used in the batch experiments. Therefore, there were a total of 9 $FeCl_3$ solutions that needed to be prepared. Firstly, the required amount of concentrated $FeCl_3$ solution and 300 mL of DI water were added into a beaker. Next, a pH meter probe was dipped into the solution to obtain its real-time pH value constantly. Then, 0.1 M of HCl, 0.1 M of NaOH, and DI water were carefully added to the solution to obtain a 500 mL $FeCl_3$ solution with a desirable concentration and pH value.

3.5.2 Preparation of Synthetic Polluted River Water

Since the target metal to be removed in the experiment is Fe^{3+}, its concentration was set to be higher than usual, which was 15 mg/L (43.57 mg/L of $FeCl_3$). The details and contents of the synthetic polluted river water prepared by using DI water and various chemical compounds are presented in Table 3.2 below.

Table 3.2: Contents of Synthetic River Water. (Smith et al., 2002)

Chemicals/ Substances	**Chemical Formula**	**Concentration (mg/L)**
Ammonium Chloride	NH_4Cl	38.0
Iron (III) Chloride	$FeCl_3$	43.57
Sodium Acetate	$C_2H_3NaO_2$	10.25
Monopotassium Phosphate	KH_2PO_4	0.36
Calcium Chloride	$CaCl_2$	136.0
Magnesium Sulphate Heptahydrate	$MgSO_4 \cdot 7H_2O$	123.2
Yeast Extract	-	2.5
Mud		2000.0

The appearance of the synthetic river water is shown in **Figure 3.4** below:

Figure 3.4: Prepared Synthetic Polluted River Water.

3.6 Experimental Procedure

At first, two types of batch experiments were performed, which included the adsorption of Fe^{3+} using various fruit peels under different conditions as well as the evaluation of the antimicrobial activity of the AC coated with silver nanoparticles. Lastly, the proposed portable filter house was set up in order to study its efficiency in purifying the synthetic polluted river water.

3.6.1 Batch Experiments for the Removal of Fe^{3+}Using Different Fruit Peels

The ground orange, banana and dragon fruit peels were weighed and packed into teabags separately with a weight of 1 g. Although the immobilization of fruit peels using teabags would negatively affect the mass transfer and biosorption efficiency, it is often considered in real-life practice as it helps to ease the handling procedure and reduce the contamination of treated water caused by fine particles.

Then, a beaker, a magnetic stirrer and a magnetic bar were set up for the batch experiment. One of the $FeCl_3$ solutions prepared in **Section 3.5.1** was measured at 100 mL and poured into the beaker. Subsequently, a teabag containing 1 g of orange peels was submerged into the beaker for 30 minutes under mild agitation. **Figure 3.5** below shows the actual experimental setup.

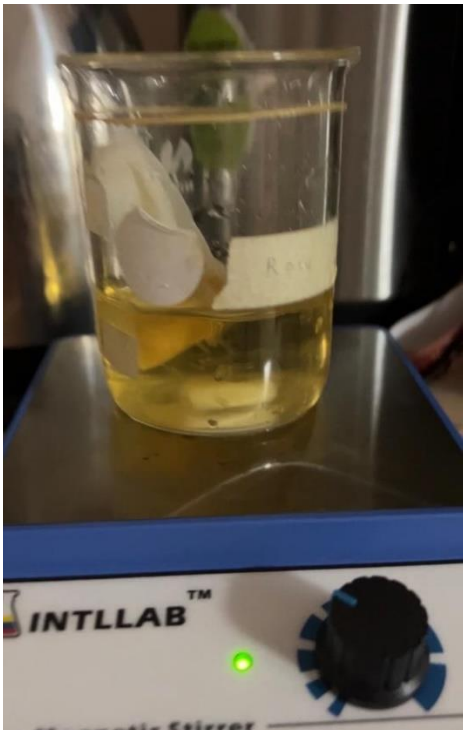


Figure 3.5: Fe^{3+} Biosorption Setup for Batch Experiments.

The experiment was then repeated using banana peels and dragon fruit peels respectively until all the prepared $FeCl_3$ solutions had been subjected to the adsorption treatment by each type of fruit peels

Next, the original and treated $FeCl_3$ solutions were analysed using the ICP-OES technique in order to determine the performance of fruit peels in removing Fe^{3+} under different conditions. The results were then analysed using Design Expert in order to investigate the correlations between each parameter. Finally, the fruit peels before and after the biosorption were subjected to FTIR analysis to study the changes in their surface properties and functional groups.

3.6.2 Antimicrobial Testing of Activated Carbon Coated with Silver Nanoparticles

First, the glassware and tools were sterilised using 80 % v/v ethanol and were subjected to UV light for 10 mins. Then, 1 L of Luria-Bertani (LB) agar solution was prepared and autoclaved for 20 mins. The autoclaved LB agar solution was then immediately poured into several Petri dishes before it solidified. The LB agar plates were then inverted and left for 1 day to let dry.

Meanwhile, a small amount of *E.coli* was added to a conical flask containing liquid Luria-Bertani broth for cultivation. The conical flask was then placed in an incubator at 37 °C for 1 day.

On the next day, the LB broth with *E.coli* underwent 10 serial dilutions. 0.1 mL of each diluted sample was added to the prepared LB agar plates. The plates were incubated for another 1 day at 37 °C in order to determine the most suitable dilution factor for observation.

The diluted LB broth with *E.coli* with the most desirable dilution factor was then spread onto several LB agar plates. Subsequently, a corer was used to make wells on the LB agar plate. Next, regular AC and AC coated with silver nanoparticles were placed into the wells. These plates were then incubated at 37 °C for 1 day. A zone of inhibition would be observed if the material exhibits antibacterial properties. Finally, the regular AC and AC coated with silver nanoparticles were analysed using SEM.

3.6.3 Final Filtration Experiment Using the Proposed Water Purification System

The biosorption filter was set up by following the filter design mentioned in **Section 3.1**. The filter consisted of 5 types of filter media, which were large and small pieces of corn cobs, AC coated with Ag, fruit peels, and 0.6 – 1.2 mm sand. The large and small pieces of corn cobs were used to remove suspended solids and big particulates such as mud. They could also help to adsorb some soluble contaminants in the water due to their porous nature. Next, the AC coated with Ag was used to remove organic, chlorinated substances and some metallic contaminants. It was also used to disinfect water in this experiment. Subsequently, the fruit peels (orange, dragon fruit, and banana peels) were mainly used to adsorb metallic contaminants such as Fe^{3+} from the water.

Besides, they were placed at the second-last layer to adsorb the Ag that might escape from the AC. Lastly, fine sand was used to capture the remaining suspended solids and leaked pieces of biosorption materials. Each layer had a thickness of 1.5 cm, which can be altered in future studies for optimisation. The following figures show the content of the filter and the actual proposed portable filter house.

Large Pieces of Corn Cobs
Small Pieces of Corn Cobs
AC coated with Silver Nanoparticles
Fruit Peels
Fine Sand (0.6 – 1.2 mm)
Water Collection Drawer

Figure 3.6: Layers of Filter Medium.

Figure 3.7: Proposed Portable Water Purification System.

100 mL of the synthetic polluted river water which was prepared based on **Table 3.2** was poured into the filter. The time taken for the filtered water to reach the 80 mL mark on the water collection drawer was recorded. The experiment was repeated 2 more times using the same batch of filter media to study the trend and lifespan of the filter media. Then, the filtered water samples

were subjected to a series of water quality analysis methods to determine the performance of the designed water purification system.

3.7 Analysis of Water Quality

The synthetic polluted river water and the filtered water samples underwent several water quality analysis techniques to obtain their chemical oxygen demand (COD), pH, conductivity, turbidity and concentration of Fe^{3+} ions. The analytical techniques involved in this study are summarised in **Table 3.3** below.

Table 3.3: Water Quality Analytic Methods and Equipment.

Parameters	**Analytical Methods and Equipment**
pH	A pH probe is placed into the water sample. The pH value is obtained when the measurement stabilises
Conductivity	A conductivity probe is placed into the water sample. The conductivity value is obtained when the measurement stabilises
Turbidity	The water sample is poured into a glass holder and placed into a turbidity meter to obtain its turbidity value
COD	Spectrophotometer
Metal Concentration	ICP-OES
Microbial activity	Spread plate method (**Section 3.6.2**)

3.7.1 Measurement of COD Using a Spectrophotometer

First, an oxidising reagent which contained Cr^{3+} ions was poured into a vial. Then, 2 mL of the water sample was pipetted into the vial containing the reagent. The vial was then inverted a few times to ensure that the solution was well-mixed. After that, the vial was heated using a DRB200 reactor at 148 °C for 2 hours. Once the oxidation reaction was complete, the vial was cooled and placed into the DR3900 spectrophotometer to obtain its COD value. (Li et al., 2009)

3.7.2 ICP-OES

First, five $FeCl_3$ solutions with concentrations of 10, 20, 30, 40 and 50 mg/L were prepared to serve as the standard solutions for calibration. Then, 10 mL of the water sample was pumped through a 0.22 μm regenerated cellulose (RC) syringe filter to remove any particulate matter that might choke the pipes of the ICP-OES equipment and interfere with the analysis. Next, the sample was then analysed automatically by the ICP-OES equipment. Finally, the concentration of Fe^{3+} was displayed on the computer screen and recorded.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Evaluation of the Performance of Various Fruit Peels on Fe^{3+} Removal

4.1.1 Fe^{3+} Biosorption Results

Firstly, the $FeCl_3$ solutions prepared according to **Table 3.1** were analysed using ICP-OES to determine their actual Fe^{3+} concentrations. The results are tabulated in **Table 4.1.**

Table 4.1: Actual Fe^{3+} concentrations of the Prepared $FeCl_3$ Solutions.

pH	**Concentration of Fe^{3+}**		
	5 mg/L	**15 mg/L**	**25 mg/L**
3	4.816 mg/L	14.526 mg/L	23.926 mg/L
7	4.742 mg/L	16.144 mg/L	24.766 mg/L
11	5.081 mg/L	14.355 mg/L	23.977 mg/L

Since the differences between the stated values and the actual values were small, it was assumed that the deviation would have negligible effects on the adsorption performance of fruit peels. Therefore, the following sections will continue addressing the three concentration levels as “5 mg/L”, “15 mg/L”, and “20 mg/L”.

The following **Tables 4.2, 4.3** and **4.3** show the remaining concentration of Fe^{3+} in the water samples after treatment using various fruit peels.

Table 4.2: Remaining Concentrations of Fe^{3+} Using Orange Peels.

pH	**Concentration of Fe^{3+}**		
	5 mg/L	**15 mg/L**	**25 mg/L**
3	4.541 mg/L	3.398 mg/L	7.759 mg/L
7	2.179 mg/L	1.614 mg/L	1.428 mg/L
11	4.600 mg/L	3.440 mg/L	3.011 mg/L

Table 4.3: Remaining Concentrations of Fe^{3+} Using Dragon Fruit Peels.

pH	**Concentration of Fe^{3+}**		
	5 mg/L	**15 mg/L**	**25 mg/L**
3	2.980 mg/L	5.478 mg/L	15.406 mg/L
7	2.724 mg/L	3.688 mg/L	1.873 mg/L
11	3.634 mg/L	6.172 mg/L	8.240 mg/L

Table 4.4: Remaining Concentrations of Fe^{3+} Using Banana Peels.

pH	**Concentration of Fe^{3+}**		
	5 mg/L	**15 mg/L**	**25 mg/L**
3	2.827 mg/L	12.738 mg/L	17.931 mg/L
7	1.728 mg/L	1.645 mg/L	1.415 mg/L
11	4.106 mg/L	1.527 mg/L	5.077 mg/L

Based on the results of batch experiments shown in **Tables 4.2, 4.3,** and **4.4**, it was found that the remaining concentrations of Fe^{3+} were the lowest when the pH was 7. In addition, it was also observed that the amount of Fe^{3+} adsorbed was high when the initial concentration of Fe^{3+} was high. This is due to the increase in the frequency of collisions between Fe^{3+} and active sites, resulting in a higher probability of adsorption to the fruit peel per ion.

To determine which fruit peel has the best adsorption performance, three graphs have been plotted to compare the percentage removal of Fe^{3+} for each fruit peel.

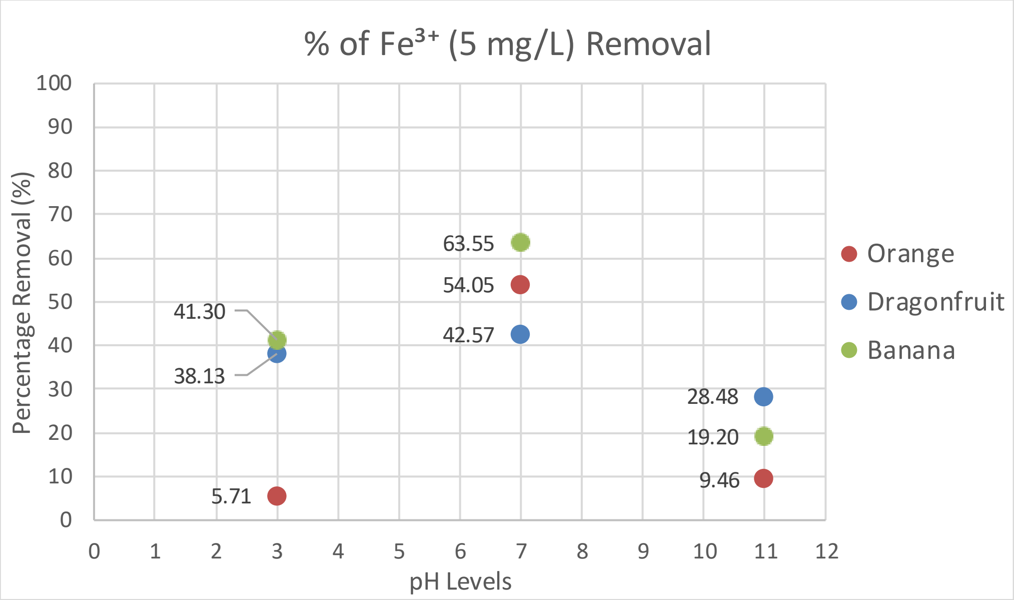


Figure 4.1: Percentage Removal of Fe^{3+} at the Concentration of 5 mg/L.

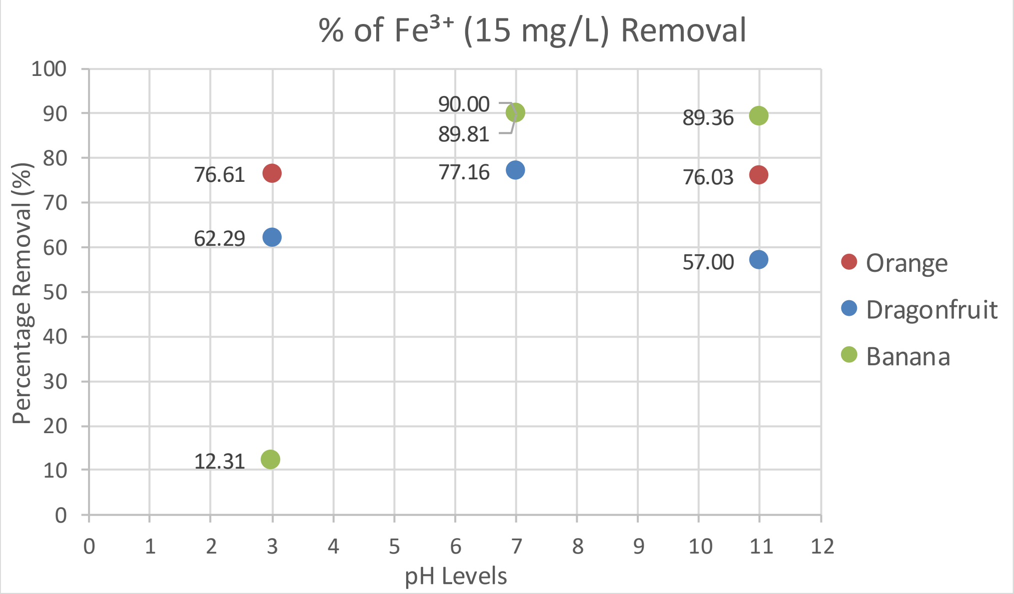


Figure 4.2: Percentage Removal of Fe^{3+} at the Concentration of 15 mg/L.

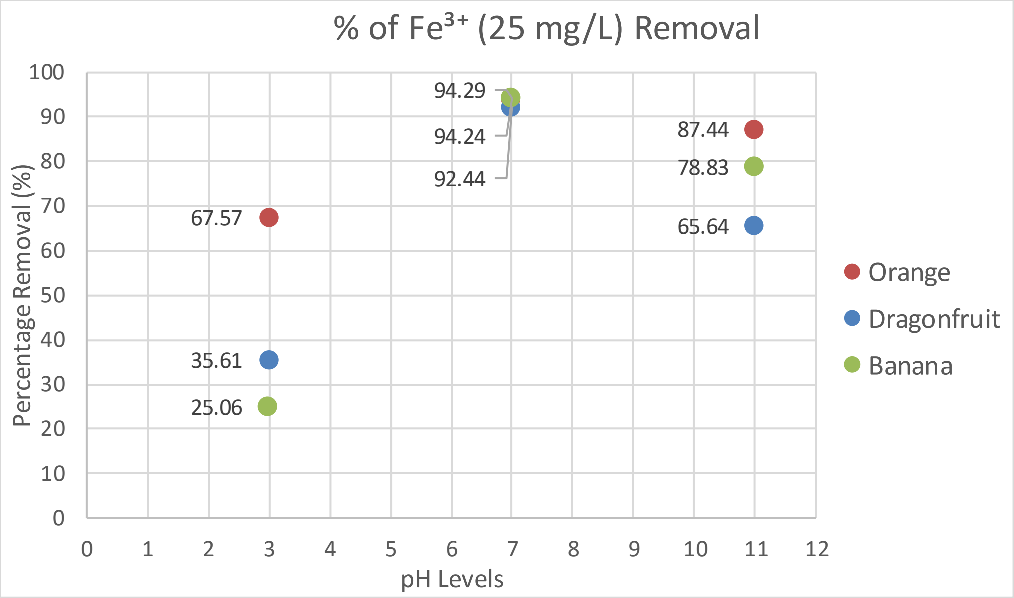


Figure 4.3: Percentage Removal of Fe^{3+} at the Concentration of 25 mg/L.

Based on the results in **Figures 4.1**, **4.2**, and **4.3** above, it was observed that the fruit peels exhibited the best biosorption performance at the pH value of 7, followed by 11 and 3 on average. When the pH value is low, the concentration of free-form H^+ in the $FeCl_3$ solution is high. These H^+ ions would compete with cationic Fe^{3+} ions for the limited adsorption sites on the fruit peel surface. As a result, the biosorption capacity is low at the pH of 3.

As the pH value increases from 3 to 7, the concentration of H^+ ions decreases and the electrostatic repulsion forces between Fe^{3+} and H^+ decreases. Meanwhile, the negative charge on the fruit peel surface also increases, which favours the adsorption of Fe^{3+} ions on the active sites. Furthermore, the deprotonation of functional groups of fruit peels such as carboxylic acids and phenols, takes place at a relatively higher pH value, which facilitates the biosorption of Fe^{3+} via the cation exchange mechanism. Therefore, the adsorption performance improves as pH increases toward the value of 7. Similar results have also been reported by Lugo-Lugo et al. (2012) and Elewa et al. (2023) for the studies of Fe^{3+} removal using pre-treated orange peels and rice husks respectively.

However, the removal efficiency dropped after pH 7 due to the interaction between Fe^{3+} and the increasing amount of OH^-, which promoted the formation of hydroxide complexes and insoluble precipitates such as $Fe(OH)_3$.

Consequently, the biosorption efficiency of fruit peels declined due to the reduction of the number of free Fe^{3+} ions present in the solution. Nevertheless, the percentage removal of Fe^{3+} at the pH of 11 was generally higher than that of pH 3 as the precipitated $Fe(OH)_3$ could easily form a sticky lump and attach to the fruit peel surfaces. Accordingly to Lugo-Lugo et al. (2012), the practical industrial wastewater treatment process actually involves the precipitation of metals by adding huge amounts of base for removal. However, this method significantly poses a great environmental concern due to the generation of hazardous sludge in large quantities, which is less sustainable than the biosorption process carried out at near-neutral pH values.

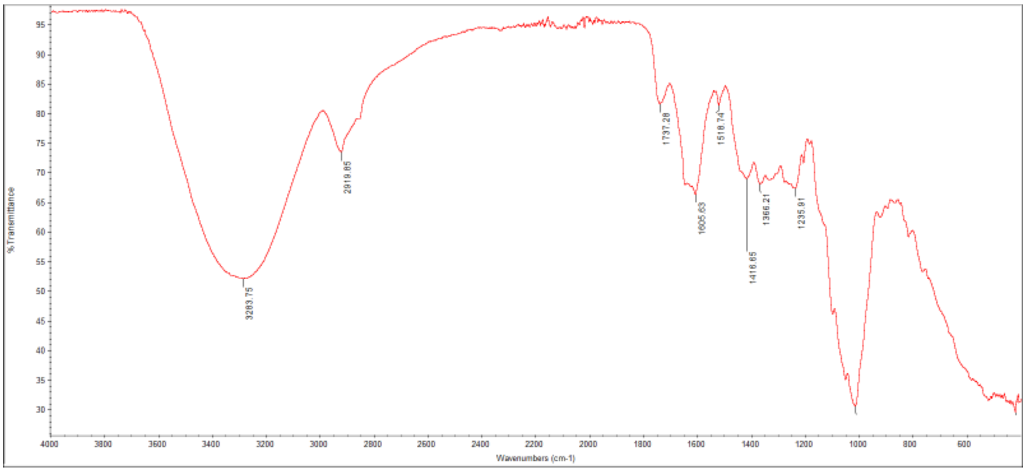
Meanwhile, it was observed that the performance of dragon fruit peels on average was poorer than orange and banana peels, whereas the performances of both of the latter fruit peels were mostly comparable under different conditions.

The chemical compositions of fruit peels differ based on species type, maturity level, location, and growing conditions. However, their major components are similar, which include lignin, cellulose, hemicellulose, pectin, starch, and soluble sugar. Each type of fruit peel contains different minor components such as fats, polyphenols, organic acids, proteins, minerals, and ash. These constituents consist of various functional groups such as hydroxyl, carboxylic, amino, carbonyl, and alkoxy groups, which exhibit good affinities for metal ions.

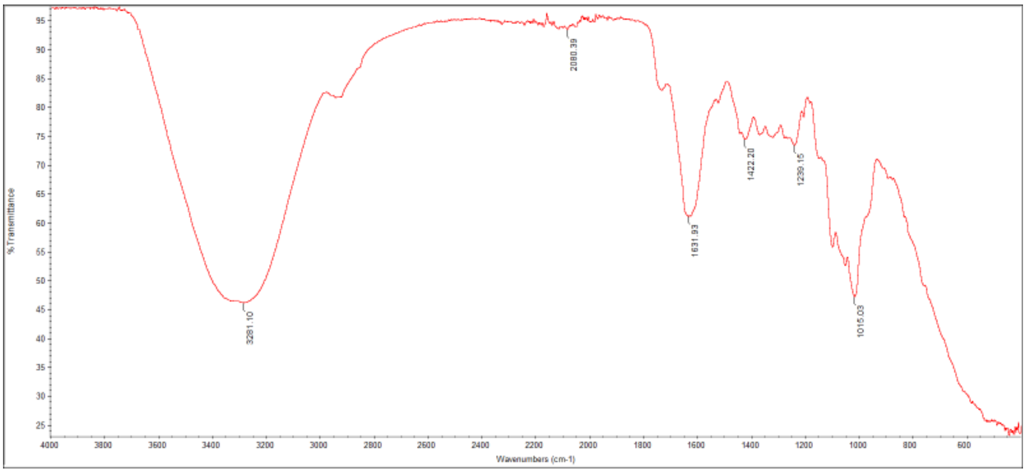
Pectin is one of the main contributors to metal adsorption due to its abundance in carboxylic groups, which makes it polar and can effectively bind to metals via chelation. Citrus fruits such as oranges, lemons and grapefruits contain the highest amount of pectin among all fruit types. According to scientific studies, orange peels contain the most pectin (30 %), followed by banana peels (15.89 – 24.08 %) and dragon fruit peels (10.79 %), which explains why orange peels show an excellent biosorption performance for Fe^{3+}. (El-Nawawi & Shehata, 1987; Khamsucharit et al., 2017; Pradana et al., 2023)

4.1.2 FTIR analysis of Fruit Peels

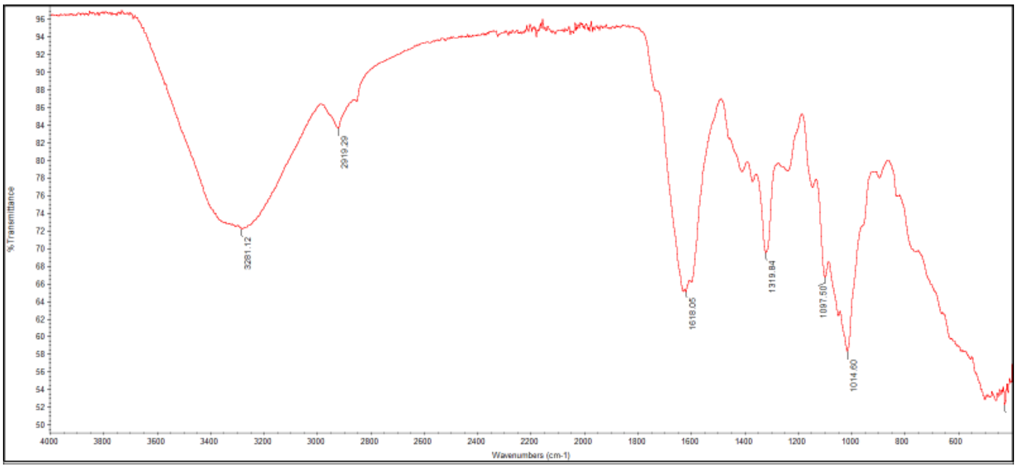
The fruit peels have been analysed by using FTIR to identify the main functional groups that partook in the biosorption of Fe^{3+}. Besides, the intensity and shape of peaks can also provide insights into the amounts of functional groups present in the fruit peels. **Figure 4.4** below shows the FTIR spectra of the above-mentioned three fruit peels before and after adsorption.



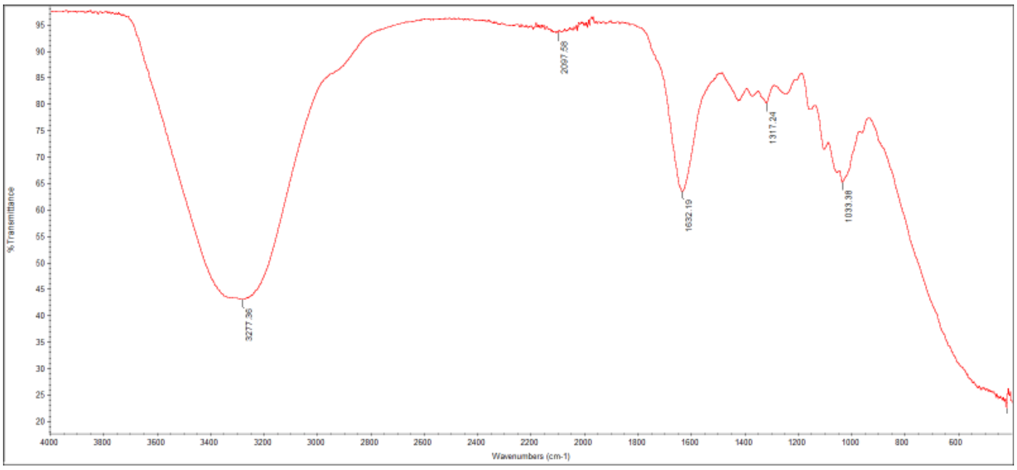
(1a)



(1b)


%Transmittance
96
94
92
90
88
86
84
82
80
78
76
74
72
70
68
66
64
62
60
58
56
54
52
50
3281.12
2919.29
1618.05
1319.84
1097.50
1014.60
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
Wavenumbers (cm-1)

(2a)


%Transmittance
95
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75
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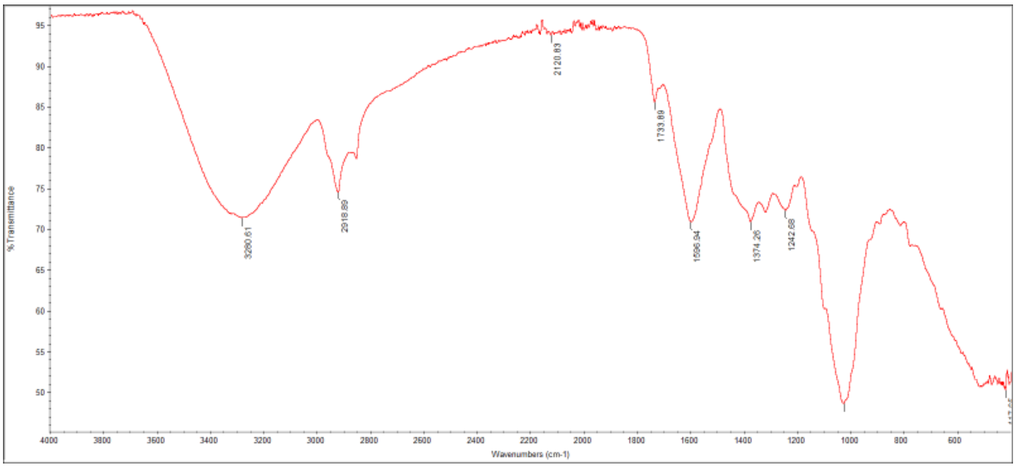
55
50
45
40
35
30
25
20
3277.36
2097.58
1632.19
1317.24
1033.38
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
Wavenumbers (cm-1)

(2b)


%Transmittance
95
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85
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75
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65
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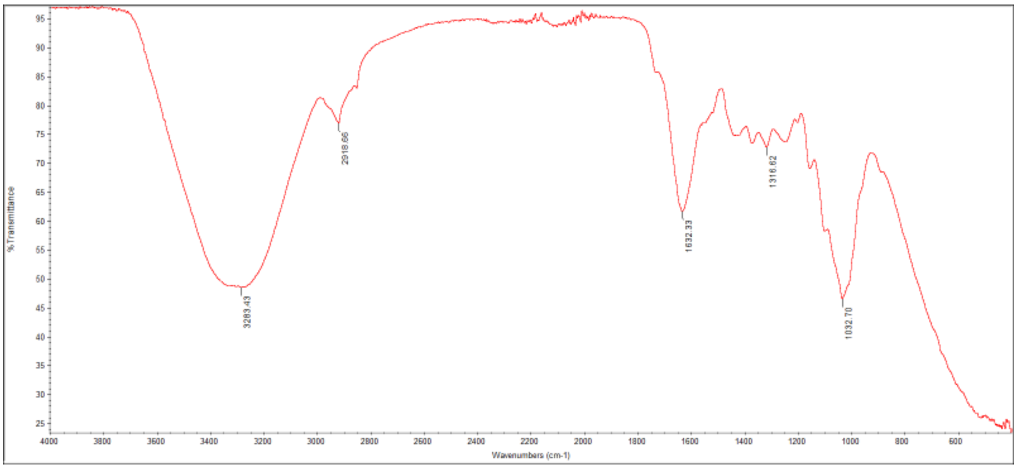
55
50
3280.61
2918.89
2120.83
1733.89
1596.94
1374.26
1242.68
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
Wavenumbers (cm-1)

(3a)



(3b)

Figure 4.4: FTIR Spectra of Orange Peels before Adsorption (1a) and after Adsorption (1b); Dragon Fruit Peels before Adsorption (2a) and after Adsorption (2b); Banana Peels before Adsorption (3a) and after Adsorption (3b).

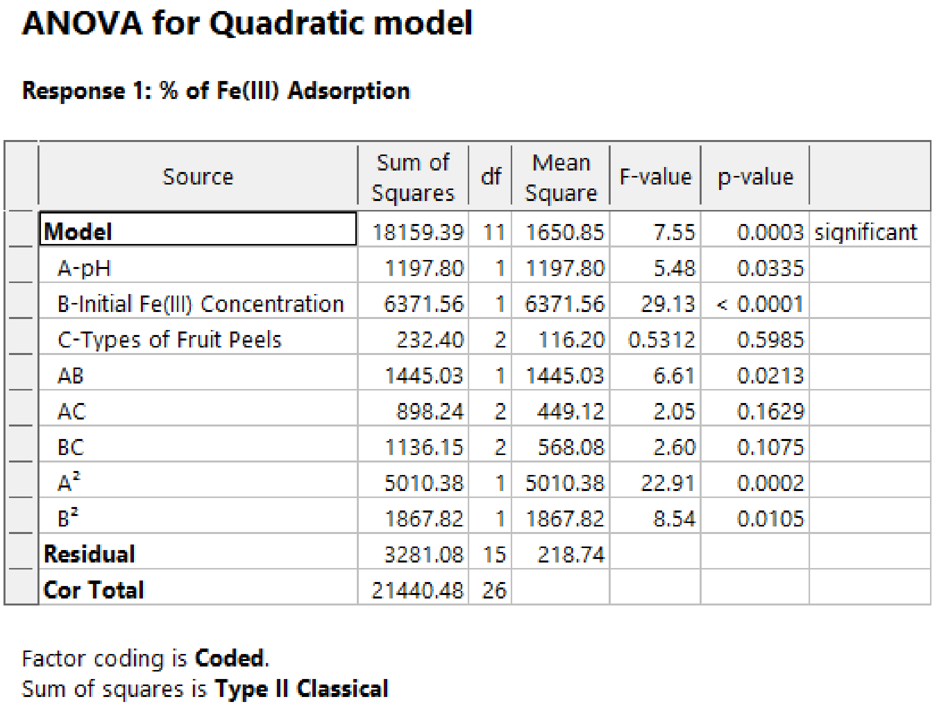
Based on **Figure 4.4 (1a)**, **(2a)** and **(3a)**, there are absorption peaks at around 3280 cm^{-1} for orange, dragon fruit, and banana peels respectively before adsorption. The peak at around 3280 cm^{-1} in **Figure 4.4 (1a)** is the widest and strongest, which indicates that there is a huge amount of O-H groups present on the surface of orange peels contributed by pectin, lignin, hemicellulose and cellulose. It can be seen that there is a change in the intensity and shape of O-H vibrations after adsorption, which implies that the O-H groups are directly involved in the binding during Fe^{3+} biosorption.

Meanwhile, the peaks at around 2919 cm^{-1} correspond to the C-H groups. The peaks decrease appreciably after adsorption, indicating that the properties of the methyl and methylene groups which are located around the active sites have been changed. This phenomenon is also observed in other studies done by Lugo-Lugo et al. (2012). From **Figure 4.4 (1a)** and **(3a)**, it is observed that both orange and banana peels show a stretching vibration at around 1735 cm^{-1}, which disappears after biosorption. This peak is contributed by the C=O groups from carboxylic acid and acetate groups. The three fruit peels have absorption peaks at around 1610 cm^{-1}, indicating the presence of C=O groups but from the carboxylate groups. The intensity of peaks decreases slightly after biosorption.

Meanwhile, there is a peak which is only shown in the FTIR spectra of orange peels before and after adsorption, which is located at around 1420 cm^{-1}. It is assigned to the asymmetric C-H groups. Lastly, all fruit peels have peaks at around 1300 cm^{-1} and 1025 cm^{-1}, which are contributed by various C-O groups such as phenolic, carboxylic acid, ether, ester, and alcoholic compounds. The changes in transmittance after adsorption imply that some of these compounds are actively involved in the biosorption of Fe^{3+}. It is also worth noting that the initial intensities of peaks at around 1025 cm^{-1} for both orange and banana peels are greater than the dragon fruit peels, suggesting that they contain relatively more active sites than dragon fruits. In short, the results show that these three peels contain abundant functional groups that can bind with metallic ions. (Chen et al., 2018)

4.1.3 Analysis of Fe^{3+} Biosorption Results Using Design Expert

The batch experiment results were imported into Design Expert to find the correlation between each variable and develop a model that can predict the performance of each fruit peel under different conditions. The following figure illustrates the analysis result.



ANOVA for Quadratic model

Response 1: % of Fe(III) Adsorption

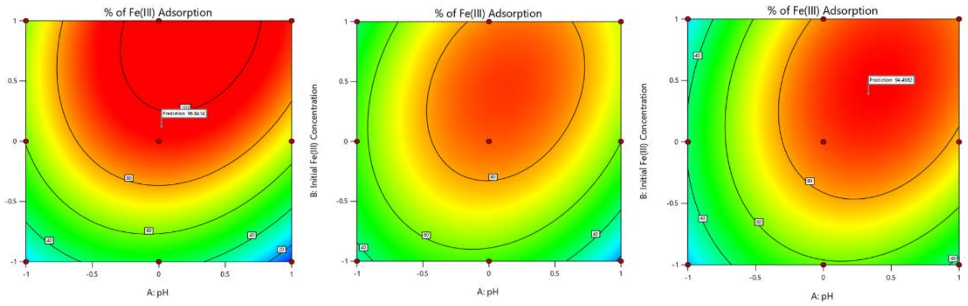
Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	18159.39	11	1650.85	7.55	0.0003	significant
A-pH	1197.80	1	1197.80	5.48	0.0335	
B-Initial Fe(III) Concentration	6371.56	1	6371.56	29.13	< 0.0001	
C-Types of Fruit Peels	232.40	2	116.20	0.5312	0.5985	
AB	1445.03	1	1445.03	6.61	0.0213	
AC	898.24	2	449.12	2.05	0.1629	
BC	1136.15	2	568.08	2.60	0.1075	
A^2	5010.38	1	5010.38	22.91	0.0002	
B^2	1867.82	1	1867.82	8.54	0.0105	
Residual	3281.08	15	218.74			
Cor Total	21440.48	26				

Factor coding is **Coded**.
Sum of squares is **Type II Classical**

Figure 4.5: ANOVA Results.

The performance of Fe^{3+} removal can be expressed as a quadratic model. The Model F-value of 7.55 indicates that the model is significant and is able to predict the percentage removal of Fe^{3+} well. There is only a 0.03 % chance that this desirable F-value is contributed by noise. Meanwhile, p-values less than 0.05 signifies that the terms are significant. In this study, the significant model terms include pH (A), concentration (B), AB, A^2, and B^2. The types of fruit peels are not as significant as other terms because fruit peels are mainly made of similar chemical compounds as explained in **Section 4.1.2**. The only difference is that the amount and weight percentage of each chemical compound are different for each fruit peel. Besides, the fruit peels used in the experiment, especially orange and banana peels, exhibited comparable adsorption capacities under optimum conditions. Hence, the type of fruit peels is less significant in the model.

Next, several contour graphs that predict the performance of Fe^{3+} adsorption for each fruit peel have been generated by Design Expert under the numerical optimisation section. The graphs are presented in **Figure 4.6** below:



(a) (b) (c)

Figure 4.6: Contour Graphs for (a) Orange, (b) Dragon Fruit, and (c) Banana Peels.

Based on the graphs, it can be observed that the contour graph for orange peels **Figure 4.6 (a)**, has the biggest bright red region that covers the widest range of pH values, which means that orange peels can greatly adsorb Fe^{3+} under huge arrays of pH values when compared to banana and dragon fruit peels. The model predicts that the highest percentage removal of Fe^{3+} using orange peels can be 96.8414 % which is higher than other experimental values shown in **Tables 4.2**, **4.3**, **and 4.4**.

Based on **Figure 4.6 (c)**, although banana peels also have an excellent biosorption capacity, they generally perform better at pH values near neutral and above. This could be due to the difference in surface properties and interactions of functional groups present on banana peels that cause banana peels to perform poorly under acidic conditions. The predicted highest percentage removal of Fe^{3+} by banana peels is 94.4982 %.

Lastly, according to the contour graph for dragon fruit peels **Figure 4.6 (b)**, the intensity of the red-colour region is the lowest and the area is the smallest among the selected fruit peels, suggesting that dragon fruit peels are less competitive in adsorbing Fe^{3+}. This can be explained by the findings from **Section 4.1.1**, where the orange peels were found to contain more pectin than dragon fruit peels, which is a compound that can effectively bind to metallic contaminants. Besides, **Section 4.1.2** also found that orange and banana peels contained relatively more active sites than dragon fruits. Therefore, dragon fruit peels have been outshined by orange and banana peels in terms of Fe^{3+} removal.

4.1.4 Summary of Batch Experiment Results

In short, it was found that the most suitable pH value for Fe^{3+} biosorption was 7. Besides, the biosorption capability increased when the initial concentration of the target contaminant (Fe^{3+}) increased, which is in accordance with the research results presented by Bilal, Ihsanullah, Younas, and Ul Hassan Shah (2021). According to the ANOVA analysis results, the pH value and initial concentration significantly affected the biosorption efficiency. However, the analysis results suggested that the type of fruit peels is insignificant as they exhibited comparable performances under optimum conditions. Therefore, orange, dragon fruit and banana peels are good candidates for Fe^{3+} removal despite the relatively lower biosorption capacity of dragon fruit peels. Therefore, a mixture of the above-mentioned fruits was used in the subsequent experiment as biosorbents to treat synthetic polluted river water.

4.2 Evaluation of Antimicrobial Activity of AC Coated with Silver Nanoparticles

4.2.1 SEM Analysis

SEM was used to examine the surfaces of the regular AC and AC coated with silver (Ag) nanoparticles to determine whether the coating process was successful. The micrographs are shown in **Figure 4.7**

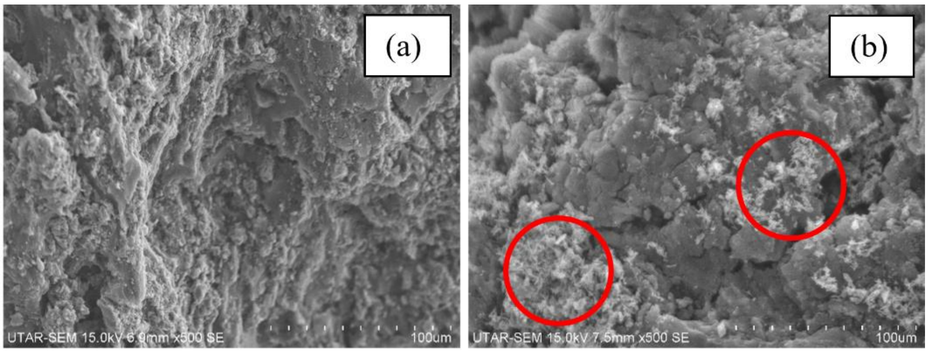


Figure 4.7: SEM Images Obtained at 500 x Magnification of (a) Regular AC, and (b) AC coated with Ag nanoparticles (Circled in Red).

It can be seen that the Ag nanoparticles are deposited onto the rough surface of AC. They appear as flakes with a brighter tone under 500 x magnification. The micrographs show that the Ag nanoparticles are evenly distributed throughout the surface in the form of patches. Hence, a potential biosorption material with antimicrobial properties has been successfully developed.

4.2.2 Spread Plate Results

Serial dilutions were performed on the LB broth containing *E.coli* in order to determine the most suitable serial dilution number. The spread plate results are shown in **Figure 4.8** below:

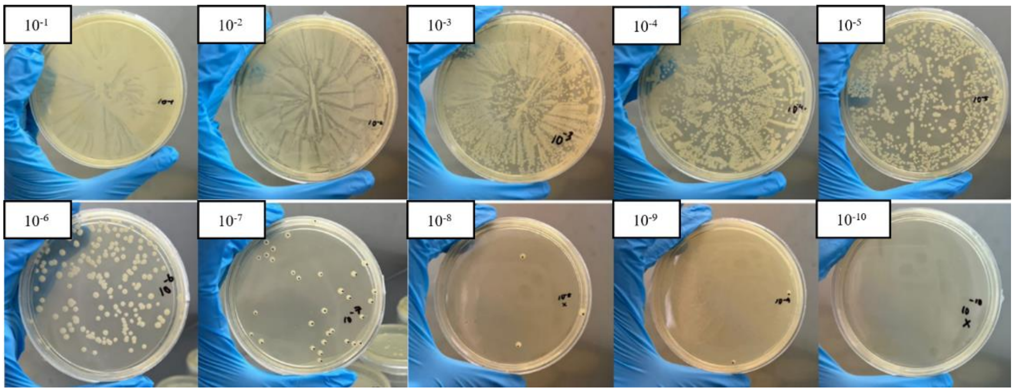


Figure 4.8: 10 Serial Dilution Results of LB Broth Containing *E.coli*.

Based on the spread-plate results, it is determined that the most desirable serial dilution number is 10^{-4} as the colonies were able to cover the whole plate and can be observed clearly. They were less dense than the plates with serial dilution numbers of 10^{-1}, 10^{-2}, and 10^{-3}. Although the number of colonies was harder to count when compared to the plates with higher dilution numbers, the study of the number of colonies was not important as this was a qualitative test. Hence, the dilution number of 10^{-4} was chosen for the testing of the antimicrobial function of the AC coated with Ag. The results are presented in **Figure 4.9** below:

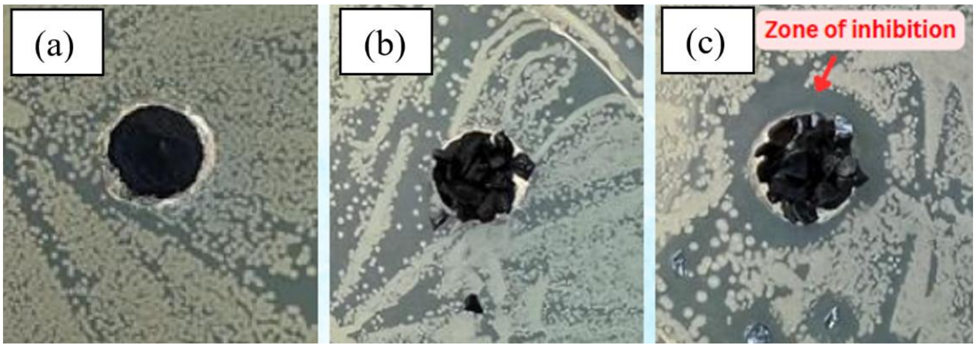


Figure 4.9: Spread Plate Results of (a) Blank, (b) Regular AC, (c) AC coated with Ag nanoparticles.

In **Figure 4.9 (a)**, it can be seen that the *E.coli* grew around the well. In **Figure 4.9 (b)**, the E.coli was able to grow alongside the regular AC, implying that the regular AC was not able to inhibit the growth of *E.coli*. Meanwhile in **Figure 4.9 (c)**, it is clear that the AC coated with Ag exhibited an antibacterial property as a zone of inhibition was observed. Ag possesses the capability to attach to the cellular membrane of bacteria, resulting in the destabilization of the cell membrane and ultimately culminating in the bacterium's demise. Moreover, Ag can penetrate the cell and impede its metabolic processes, causing a disruption in its proper functioning. Therefore, *E.coli* was not able to grow around the AC coated with Ag due to Ag's antibacterial properties. (Chandra Joshi et al., 2022)

4.3 Evaluation of the Performance of the Proposed Portable Water Purification System

The appearance of the synthetic polluted water and treated water samples are shown in **Figure 4.10** below for comparison.

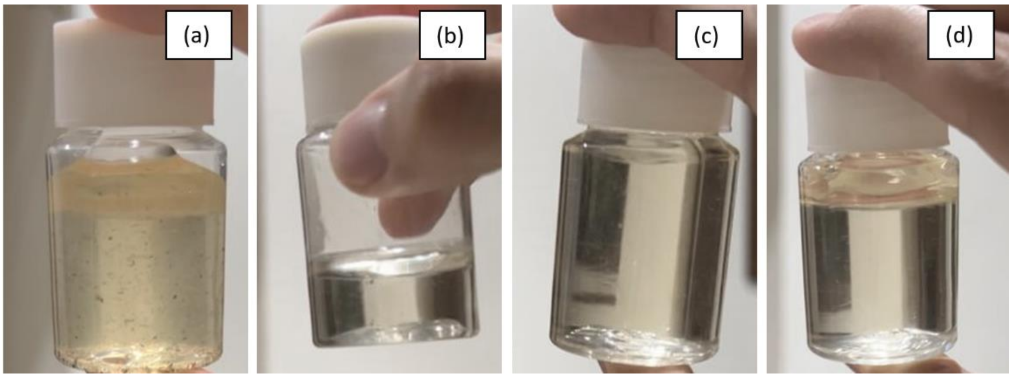


Figure 4.10: Physical Appearance of (a) Synthetic Polluted Water, (b) 1st Batch of Filtered Water, (c) 2nd Batch of Filtered Water, (d) 3rd Batch of Filtered Water.

Apparently, it can be seen that the suspended solids present in **Figure 4.10 (a)** have been effectively removed. Besides, the intensities of the yellow colour contributed by the Fe^{3+} are lower in **Figure 4.10 (b)**, **(c)**, and **(d)** when compared to **Figure 4.10 (a)**, implying that the proposed filter media were able to capture Fe^{3+} ions. Next, the qualities of the treated synthetic polluted river water samples were accessed using different techniques. The results are tabulated in **Table 4.5** below, which also includes the time taken to collect 80 mL of purified water, water flow rates and fluxes.

Table 4.5: Purified Water Analysis Results.

Parameters	**Filtered Water Samples**		
	1st Filtration	**2nd Filtration**	**3rd Filtration**
Time Taken to Collect 80 mL of Treated Water (s)	89.7	111.7	85.6
Flow Rate (mL/s)	0.8919	0.7162	0.9346
Water Flux (L/m^{2}h)	526.32	422.64	551.52
pH	5.76	4.96	4.85
Conductivity (µs/cm)	44	104	167
Turbidity (NTU)	13.2	20.1	16.8
COD (mg/L)	156	98	124
Fe^{3+} Concentration (mg/L)	0.185	0.211	0.207

The proposed filtration system provided a flow rate of 0.8475 mL/s on average. The cross-sectional area of the proposed system was 0.0061 m^2, and the average water flux was 500.16 L/m^{2}h. Meanwhile, the portable water filters currently available on the market that utilise membrane technology include "Membrane Solutions Portable Squeeze Water System" and "Simpure Outdoor Gravity Portable Water Purifier". Both filters provide water fluxes of 118 434.61 L/m^{2}h and 16 230.84 mL/s respectively, which are significantly better than the proposed filtration system. The former product requires the user to suck through the straw to create a pressure difference, which allows it to have a higher flux. The latter product only uses gravity as its driving force, which is similar to the proposed filter. Therefore, more improvements should be made to the current model in terms of filter media allocation and filter housing design to increase its flow rate and flux so that the product can be more practical in the actual situation. (SimPure, 2022)

The acidity of the synthetic polluted water was mainly contributed by $FeCl_3$ as it underwent hydrolysis in the water and formed HCl. On the other hand, the conductivity value is able to provide some insight into the amounts of dissolved solids present in the water. Based on **Table 4.5**, it was observed that the pH values of treated water samples were decreasing, whereas the conductivity values were increasing. This could be due to the saturation of the biosorption material because more active sites were occupied by various substances, including Fe^{3+}, Cl^-, and NH^{4+} as the filter usage time increased. Therefore, the contaminants that were not successfully adsorbed by the filter media would result in a reduction in pH and increment in conductivity values when the same filter media were used again without backwashing and replacement.

In addition, it can be seen that the performance of Fe^{3+} removal was consistent. However, there were fluctuations in the COD values of the filtered water. Hence, the average values of these parameters were obtained and compared with the untreated water as well as the Malaysian drinking water standards for a better evaluation. The results are summarised in **Table 4.6** below:

Table 4.6: Comparison between Water Purification Results Based on Various Parameters. (MOH, 2004)

Parameters	**Malaysian Drinking Water Standards**	**Synthetic Polluted Water**	**Purified Water (Average)**
pH	6.50 – 9.00	4.34	5.19
Conductivity (µs/cm)	< 800	175	105
Turbidity (NTU)	5.0	91.4	16.7
COD (mg/L)	10	51	126
Fe^{3+} Concentration (mg/L)	0.300	14.587	0.201

Based on **Table 4.6**, although the pH of the polluted water was improved, the result showed that the treated water was not able to meet the minimum requirement stated in the Malaysian drinking water standards.

Meanwhile, the proposed filtration system was able to reduce the conductivity of the polluted water, which implied that the filter media had successfully adsorbed some of the dissolved contaminants. According to Malaysian drinking water standards, the maximum accepted conductivity value is 800 µs/cm. Although the initial conductivity value of the untreated polluted water already fulfils the requirement, it comes with the condition that the concentration of each chemical constituent must be below the maximum value and it does not cause adverse health effects to humans when ingested. In other words, a water sample with a conductivity value that is less than 800 µs/cm does not imply that the water is safe for consumption.

Based on **Figure 4.10** and **Table 4.6**, the filter could remove most of the suspended solids as the turbidity of the polluted water had been effectively reduced. Nevertheless, the purified water was not treated to a potable standard. Besides, the filtration system seemed to significantly increase the COD instead, which implied that there was a leakage of fine organic matter from ground fruit peels and corn cobs into the water. Therefore, the length and depth of each filter medium must be adjusted in order to improve its performance. Furthermore, the fruit peels should also be subjected to heat and chemical treatments before being used as filter media. These treatments can help to break down their organic matter and reduce the chances of introducing COD into the treated water. (Bilal, Ihsanullah, Younas and Ul Hassan Shah, 2021)

Lastly, it was evident that the proposed filtration had a good performance in removing Fe^{3+} as the concentrations of Fe^{3+} in the treated water samples were lower than the value stated in the Malaysian drinking water standards. In short, although the proposed portable water purification system is yet to produce potable water, several improvements such as proper pre-treatment of filter media and adjustment of filter media depth can be made to achieve a better result.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In a nutshell, all fruit peels exhibited poor Fe^{3+} uptakes under acidic conditions due to high amounts of H^+ that would compete with Fe^{3+} for the binding sites. In addition, the biosorption efficiency of Fe^{3+} decreased as the pH increased beyond 7 due to the formation of insoluble $Fe(OH)_3$, which reduced the amount of free Fe^{3+} to be attached to the active sites. Hence, the most suitable pH value for Fe^{3+} biosorption was 7. The best Fe^{3+} biosorption occurred when the initial concentration of Fe^{3+} was 25 mg/L at pH 7 as the biosorption efficiency increased when the initial concentration increased. The values of the maximum percentage removal of Fe^{3+} were 94.2879 %, 94.2358 % and 92.4361 % for banana, orange and dragon fruit peels, respectively.

According to the ANOVA analysis results, it was determined that the type of fruit peels could not significantly affect the biosorption performance as they exhibited comparable efficiencies in removing Fe^{3+} under optimum conditions, implying that all the proposed fruit peels are good candidates for Fe^{3+} biosorption. Therefore, the fourth objective, which is to investigate the effects of pH values, initial concentrations, and type of fruit peels on the efficiency of Fe^{3+} removal, was fulfilled.

In the research, Ag nanoparticles were successfully coated on the AC. The material did possess antibacterial properties as a zone of inhibition was observed on the spread plate used to culture *E.coli*. Hence, the third objective was achieved. Finally, a portable, low-cost water filtration system was successfully proposed. It was able to reduce the Fe^{3+} concentration, conductivity and turbidity values of the synthetic polluted water by 98.62 %, 40.00 %, and 81.73 % respectively, proving its effectiveness in removing Fe^{3+}, TDS and suspended solids. Thus, the remaining (first and second) objectives were also accomplished. Nevertheless, further improvements are required to be made to obtain potable water with a higher flux so that the practicability of the proposed system can be enhanced.

5.2 Recommendations for Future Work

Based on the research conducted on developing a portable water purification using low-cost biomaterials, several recommendations for improvements can be implemented to address the shortcomings and enhance the overall performance of the research.

Firstly, subjecting the fruit peels to heat and chemical treatments is recommended to improve their biosorption capacity and reduce the amount of organic matter leached into the treated water. Therefore, the high COD value of filtered water can be overcome. Besides, since common industrial practices often adjust the pH of wastewater during pretreatment, the pH value of synthetic polluted water should be adjusted to the optimum pH value (which is 7) so that the performance of the proposed filter house can be evaluated under optimum conditions. Lastly, the microbial activity of the treated water should also be tested to determine the effectiveness of the modified AC during filtration.

On the other hand, the optimum filter media allocation and depth can be studied to improve the performance of the proposed filtration system. Furthermore, the adsorption efficiency of the proposed filtration system for other contaminants such as heavy metals and volatile organic compounds can also be investigated as these compounds pose a greater threat to human health.

In addition, it is also recommended to study the point of zero charge (PZC) of biosorbents as each biosorbent has its own PZC value, which is influenced by the types of functional groups and surface properties. The determination of PZC values allows researchers to predict the biosorption capacity of a biosorbent when exposed to aqueous solutions of different pH values. Therefore, the optimum pH values for each biosorbent can be determined to obtain the best adsorption result.

Besides, the biosorption mechanism and kinetics can also be investigated so that a mathematical model that can predict the performance of the biosorbent can be developed. The acquired knowledge can aid in optimising operating conditions and related parameters to increase contaminant removal efficiency. Moreover, the developed mathematical model can also be used during the designing stage of the water purification system in large-scale applications.

Finally, the reusability of the biosorbents should also be studied by determining the most suitable regeneration agent and methods to reduce the cost and improve the sustainability of the water treatment process. As a result, an economically feasible and environmentally sustainable water purification system can be successfully developed.

REFERENCES

Adams, Q., 2020. *Nutrient Pollution: How Excess Nitrogen and Phosphorus are Shaping Health Outcomes | National Caucus of Environmental Legislators*. [online] National Caucus of Environmental Legislators. Available at: <https://www.ncelenviro.org/articles/nutrient-pollution-how-excess-nitrogen-and-phosphorus-are-shaping-health-outcomes/#:~:text=There%20are%20a%20number%20of,neurological%20issues%2C%20or%20respiratory%20problems.> [Accessed 5 September 2022].

Adie, D., Lukman, S., Sani, B. and Yahaya, I., 2013. International Journal of Applied Science and Technology Vol. 3 No. 3; March 2013 146 Comparative Analysis of Filtration Using Corn Cob, Bone Char and Wood Chippings. [online] Available at: <https://www.researchgate.net/publication/255716381_Comparative_Analysis_of_Filtration_Using_Corn_Cob_Bone_Char_and_Wood_Chippings> [Accessed 7 September 2022].

Ahmad, M., Rajapaksha, A., Lim, J., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S. and Ok, Y., 2014. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere*, 99, pp.19-33.

Ambaye, T., Vaccari, M., van Hullebusch, E., Amrane, A. and Rtimi, S., 2020. Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. *International Journal of Environmental Science and Technology*, 18(10), pp.3273-3294.

Ashraf, M., Rehman, M., Alias, Y. and Yusoff, I., 2013. Removal of Cd(II) onto Raphanus sativus peels biomass: equilibrium, kinetics, and thermodynamics. *Desalination and Water Treatment*, 51(22-24), pp.4402-4412.

Ayala, J.R., Montero, G., Coronado, M.A., García, C., Curiel-Alvarez, M.A., León, J.A., Sagaste, C.A., and Montes, D.G., 2021. Characterization of orange peel waste and valorization to obtain reducing sugars. *Molecules*, 26(5), p. 1348. Available at: <https://doi.org/10.3390/molecules26051348.> [Accessed 25 April 2022].

Bhatnagar, A., Minocha, A. and Sillanpää, M., 2010. Adsorptive removal of cobalt from aqueous solution by utilizing lemon peel as biosorbent. *Biochemical Engineering Journal*, 48(2), pp.181-186.

Bilal, M., Ihsanullah, I., Younas, M. and Ul Hassan Shah, M., 2021. Recent advances in applications of low-cost adsorbents for the removal of heavy metals from water: A critical review. *Separation and Purification Technology*, 278, p.119510.

Biswas, P., and Bandyopadhyaya, R., 2016. Water disinfection using silver nanoparticle impregnated activated carbon: Escherichia coli cell-killing in batch and continuous packed column operation over a long duration. *Water Research*, 100, pp.105–115.

Cay, S.,, Uyanik, A., and Ozasik, A., 2004. Single and binary component adsorption of copper(ii) and cadmium(ii) from aqueous solutions using tea-industry waste. *Separation and Purification Technology*, 38(3), pp.273–280.

CDC, 2022. *Disinfection by-products (DBPs)*. [online] Centers for Disease Control and Prevention. Available at: <https://www.cdc.gov/biomonitoring/THM-DBP_FactSheet.html#:~:text=Disinfection%20by%2Dproducts%20(DBPs)%20are%20formed%20when%20disinfectants%20like,bathing%2C%20dishwashing%2C%20and%20swimming.> [Accessed 5 September 2022].

CDC, 2022. *Global Water, Sanitation, & Hygiene (WASH)*. [online] Centers for Disease Control and Prevention. Available at: <https://www.cdc.gov/healthywater/global/wash_statistics.html#four> [Accessed 17 August 2022].

Chandra Joshi, H., Dutta, D., Gaur, N., Singh, G.S., Dubey, R., and Dwivedi, S.K., 2022. Silver-doped active carbon spheres and their application for microbial decontamination of water. *Heliyon*, 8(4). Available at: <https://doi.org/10.1016/j.heliyon.2022.e09209.> [Accessed 29 April 2022].

Chen, X., Chen, G., Chen, L., Chen, Y., Lehmann, J., McBride, M. and Hay, A., 2011. Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. *Bioresource Technology*, 102(19), pp.8877-8884.

Chen, Y., Wang, H., Zhao, W. and Huang, S., 2018. Four different kinds of peels as adsorbents for the removal of Cd (II) from aqueous solution: Kinetics, isotherm and mechanism. *Journal of the Taiwan Institute of Chemical Engineers*, 88, pp.146-151. Available at: <https://doi.org/10.1016/j.jtice.2018.03.046.> [Accessed 29 April 2022].

Chou, F. and Wu, C., 2010. Reducing the impacts of flood-induced reservoir turbidity on a regional water supply system. *Advances in Water Resources*, 33(2), pp.146-157.

Cisneros, B., 2011. Safe Sanitation in Low Economic Development Areas. *Treatise on Water Science*, pp.147-200.

Eberhard, R., 2019. Access to Water and Sanitation in Sub-Saharan Africa. *Review of Sector Reforms and Investments, Key Findings to Inform Future Support to Sector Development*, [online] Available at: <https://www.oecd.org/water/GIZ_2018_Access_Study_Part%20I_Synthesis_Report.pdf> [Accessed 21 August 2022].

El-Aassar, A., Said, M., Abdel-Gawad, A. and Shawky, H., 2013. Using Silver Nanoparticles Coated on Activated Carbon Granules in Columns for Microbiological Pollutants Water Disinfection in Abu Rawash area, Great Cairo, Egypt. [online] Available at: <https://www.researchgate.net/publication/270588722_Using_Silver_Nanoparticles_Coated_on_Activated_Carbon_Granules_in_Columns_for_Microbiological_Pollutants_Water_Disinfection_in_Abu_Rawash_area_Great_Cairo_Egypt> [Accessed 7 September 2022].

Elewa, A.M., Amer, A.A., Attallah, M.F., Gad, H.A., Al-Ahmed, Z.A., and Ahmed, I.A., 2023. Chemically activated carbon based on biomass for adsorption of fe(iii) and mn(ii) ions from aqueous solution. *Materials*, 16(3), p. 1251. Available at: <https://doi.org/10.3390/ma16031251.> [Accessed 25 April 2022].

El-Nawawi, S.A. and Shehata, F.R., 1987. Extraction of pectin from Egyptian Orange Peel. factors affecting the extraction. *Biological Wastes*, 20(4), pp. 281–290. Available at: <https://doi.org/10.1016/0269-7483(87)90005-x.> [Accessed 25 April 2022].

FOMCA, 2021. *FOMCA, WECAM, FAM: Celebrating World Water Day 2021 – Valuing Water*. [online] Fomca.org.my. Available at: <https://www.fomca.org.my/v1/index.php/fomca-di-pentas-media/fomca-di-pentas-media-2021-21/1295-fomca-wecam-fam-celebrating-world-water-day-2021-valuing-water#:~:text=Based%20on%20statistics%20from%20National,recommended%20by%20The%20United%20Nations.> [Accessed 17 August 2022].

Fuller, R., Landrigan, P., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., Caravanos, J., Chiles, T., Cohen, A., Corra, L., Cropper, M., Ferraro, G., Hanna, J., Hanrahan, D., Hu, H., Hunter, D., Janata, G., Kupka, R., Lanphear, B., Lichtveld, M., Martin, K., Mustapha, A., Sanchez-Triana, E., Sandilya, K., Schaefli, L., Shaw, J., Seddon, J., Suk, W., Téllez-Rojo, M. and Yan, C., 2022. Pollution and health: a progress update. *The Lancet Planetary Health*, 6(6), pp.e535-e547.

Guechi, E. and Hamdaoui, O., 2015. Evaluation of potato peel as a novel adsorbent for the removal of Cu(II) from aqueous solutions: equilibrium, kinetic, and thermodynamic studies. *Desalination and Water Treatment*, 57(23), pp.10677-10688.

Herrera-Barros, A., Tejada-Tovar, C., and González-Delgado, Á.D., 2022. Green nanoparticle-aided Biosorption of nickel ions using four dry residual biomasses: A comparative study. *Sustainability*, 14(12), p.7250.

Herrera-Barros, A., Tejada-Tovar, C., Villabona-Ortíz, A., González-Delgado, A. and Benitez-Monroy, J., 2020. Cd (II) and Ni (II) uptake by novel biosorbent prepared from oil palm residual biomass and Al2O3 nanoparticles. *Sustainable Chemistry and Pharmacy*, 15, p.100216.

Jaafar, A., Darchen, A., Hamzi, S., Lakbaibi, Z., Driouich, A., Boussaoud, A., Yaacoubi, A., El Makhfouk, M. and Hachkar, M., 2021. Optimization of cadmium ions biosorption by fish scale from aqueous solutions using factorial design analysis and Monte Carlo simulation studies. *Journal of Environmental Chemical Engineering*, 9(1), p.104727.

Khalid, M. and Abdollahi, M., 2021. Environmental Distribution of Personal Care Products and Their Effects on Human Health. [online] Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8170769/> [Accessed 5 September 2022].

Khamsucharit, P., Laohaphatanalert, K., Gavinlertvatana, P., Sriroth, K., and Sangseethong, K., 2017. Characterization of pectin extracted from banana peels of different varieties. *Food Science and Biotechnology*, 27(3), pp. 623–629. Available at: <https://doi.org/10.1007/s10068-017-0302-0.> [Accessed 25 April 2022].

Khatoon, H. and Rai, J., 2016. AGRICULTURAL WASTE MATERIALS AS BIOSORBENTS FOR THE REMOVAL OF HEAVY METALS AND SYNTHETIC DYES– A REVIEW. [online] Available at: <https://www.researchgate.net/publication/327051571_AGRICULTURAL_WASTE_MATERIALS_AS_BIOSORBENTS_FOR_THE_REMOVAL_OF_HEAVY_METALS_AND_SYNTHETIC_DYES-_A_REVIEW> [Accessed 18 August 2022].

Kumar, A., Kumar, A., Sharma, G., Naushad, M., Stadler, F., Ghfar, A., Dhiman, P. and Saini, R., 2017. Sustainable nano-hybrids of magnetic biochar supported g-C 3 N 4 /FeVO 4 for solar powered degradation of noxious pollutants- Synergism of adsorption, photocatalysis & photo-ozonation. *Journal of Cleaner Production*, 165, pp.431-451.

Kumar, M., Borah, P. and Devi, P., 2020. Priority and emerging pollutants in water. *Inorganic Pollutants in Water*, pp.33-49.

Kumar, P. and Chauhan, M., 2019. Adsorption of chromium (VI) from the synthetic aqueous solution using chemically modified dried water hyacinth roots. *Journal of Environmental Chemical Engineering*, 7(4), p.103218.

Lee, J., Perera, D., Glickman, T. and Taing, L., 2020. Water-related disasters and their health impacts: A global review. Progress in Disaster Science, 8, p.100123.

Lee, S.-Y., and Choi, H.-J., 2018. Persimmon leaf bio-waste for adsorptive removal of heavy metals from aqueous solution. *Journal of Environmental Management*, 209, pp.382–392.

Li, J., Tao, T., Li, X., Zuo, J., Li, T., Lu, J., Li, S., Chen, L., Xia, C., Liu, Y. and Wang, Y., 2009. A spectrophotometric method for determination of chemical oxygen demand using home-made reagents. *Desalination*, 239(1-3), pp.139-145.

Lu, H., Zhang, W., Yang, Y., Huang, X., Wang, S. and Qiu, R., 2012. Relative distribution of Pb2+ sorption mechanisms by sludge-derived biochar. *Water Research*, 46(3), pp.854-862.

Lugo-Lugo, V., Barrera-Diaz, C., Urena-Nunez, F., and Linares-Hernandex, I., 2012. Biosorption of cr(iii) and fe(iii) in single and binary systems onto pretreated Orange Peel. *Journal of Environmental Management*, 112, pp. 120–127. Available at:< https://doi.org/10.1016/j.jenvman.2012.07.009.> [Accessed 25 April 2022].

Ma, Y., Liu, W., Zhang, N., Li, Y., Jiang, H. and Sheng, G., 2014. Polyethylenimine modified biochar adsorbent for hexavalent chromium removal from the aqueous solution. *Bioresource Technology*, 169, pp.403-408.

Mavrouli, M., Mavroulis, S., Lekkas, E. and Tsakris, A., 2021. Respiratory Infections Following Earthquake-Induced Tsunamis: Transmission Risk

Factors and Lessons Learned for Disaster Risk Management. *International Journal of Environmental Research and Public Health*, 18(9), p.4952.

MOH, 2004. *National Standard for Drinking Water Quality*. [online] Available at: <http://www.gunungganang.com.my/pdf/Malaysian-Policies-Standards-Guidelines/Standards/National%20Drinking%20Water%20Quality%20Standard.pdf> [Accessed 10 September 2022].

Moyo, M., Pakade, V. and Modise, S., 2017. Biosorption of lead(II) by chemically modified Mangifera indica seed shells: Adsorbent preparation, characterization and performance assessment. *Process Safety and Environmental Protection*, 111, pp.40-51.

Mukherjee, A., Zimmerman, A. and Harris, W., 2011. Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma*, 163(3-4), pp.247-255.

Olagoke, O. and Awojobi, K., 2018. Isolation and Characterization of Stream Water Bacteria from ESA-OKE Metropolis. *Journal of Medical Microbiology & Diagnosis*, 07(02).

Pradana, D.W., Manab, A. and Sawitri, M.E., 2023. Emulsion properties of synbiotic yoghurt red dragon fruit peel extract (Hylocereus Polyrhizus) evaporation with honey. *Asian Food Science Journal*, pp. 19–24. Available at: <https://doi.org/10.9734/afsj/2023/v22i1612.> [Accessed 29 April 2022].

Reynolds, K., 2005. *Waterborne Disease Outbreaks following Tsunami Disaster*. [online] WCP Online. Available at: <https://wcponline.com/2005/02/17/waterborne-disease-outbreaks-following-tsunami-disaster/> [Accessed 19 August 2022].

Sauvé, S. and Desrosiers, M., 2014. A review of what is an emerging contaminant. *Chemistry Central Journal*, 8(1).

See, K., Nayan, N. and Rahaman, Z., 2017. Flood Disaster Water Supply: A Review of Issues and Challenges in Malaysia. *International Journal of Academic Research in Business and Social Sciences*, 7(10).

Semerjian, L., 2018. Removal of heavy metals (Cu, Pb) from aqueous solutions using pine (Pinus halepensis) sawdust: Equilibrium, kinetic, and thermodynamic studies. *Environmental Technology & Innovation*, 12, pp.91-103.

Siddiqui, A.J.,, Kumari, N.,, Adnan, M.,, Kumar, S.,, Abdelgadir, A.,, Saxena, J.,, Badraoui, R.,, Snoussi, M.,, Khare, P., and Singh, R., 2023. Impregnation of modified magnetic nanoparticles on low-cost agro-waste-derived biochar for enhanced removal of pharmaceutically active compounds: Performance evaluation and optimization using response surface methodology. *Water*, 15(9), p.1688.

SimPure, 2022. The 5 best outdoor portable water filter in 2022, SimPure. SimPure. Available at: <https://www.simpurelife.com/blogs/blogs/outdoor-portable-water

filter#:~:text=This%20outdoor%20portable%20water%20filter's,min)%20while%20maintaining%20filtration%20accuracy.> [Accessed 29 April 2022].

Smith, E.J., Davison, W. and Hamilton, T.J., 2002. Methods for preparing synthetic freshwaters. *Water Research*, 36(5), pp. 1286-1296.

Taha, A., Ben Aissa, M. and Da'na, E., 2020. Green Synthesis of an Activated Carbon-Supported Ag and ZnO Nanocomposite for Photocatalytic Degradation and Its Antibacterial Activities. *Molecules*, 25(7), p.1586.

Tanasal, A.M., Nafie, N.L. and Taba, P., 2015. BIOSORPTION OF Cd(II) ION BY DRAGON FRUIT PEEL, *Indonesia Chimica Acta*, 8(1). Available at: https://doi.org/https://doi.org/10.20956/ica.v8i1.2478. [Accessed 25 April 2023].

Tatlock, C., 2006. *Water Stress in Sub-Saharan Africa*. [online] Council on Foreign Relations. Available at: <https://www.cfr.org/backgrounder/water-stress-sub-saharan-africa> [Accessed 21 August 2022].

Tchounwou, P., Yedjou, C., Patlolla, A. and Sutton, D., 2012. Heavy Metal Toxicity and the Environment. *Experientia Supplementum*, pp.133-164.

UNICEF, 2019. *1 in 3 people globally do not have access to safe drinking water – UNICEF, WHO*. [online] Unicef.org. Available at: <https://www.unicef.org/eap/press-releases/1-3-people-globally-do-not-have-access-safe-drinking-water-unicef-who> [Accessed 17 August 2022].

Venkatesha, R., Rao, A. and Kedare, S., 2014. Portable Water Purifiers. [online] Available at: <https://www.researchgate.net/publication/301547870_Portable_Water_Purifiers> [Accessed 17 August 2022].

Vision of Humanity, 2020. *Increase in Natural Disasters on a Global Scale by Ten Times*. [online] Available at: <https://www.visionofhumanity.org/global-number-of-natural-disasters-increases-ten-times/#:~:text=Data%20captured%20between%201900%20and,1960%20to%20396%20in%202019.> [Accessed 19 August 2022].

Yang, S., Wu, Y., Aierken, A., Zhang, M., Fang, P., Fan, Y. and Ming, Z., 2016. Mono/competitive adsorption of Arsenic(III) and Nickel(II) using modified green tea waste. *Journal of the Taiwan Institute of Chemical Engineers*, 60, pp.213-221.

Zbair, M., Ait Ahsaine, H., Anfar, Z. and Slassi, A., 2019. Carbon microspheres derived from walnut shell: Rapid and remarkable uptake of heavy metal ions, molecular computational study and surface modeling. *Chemosphere*, 231, pp.140-150.