AMERICAN UNIVERSITY OF BEIRUT

ENHANCING WATER SAFETY THROUGH THE USE OF ECOFRIENDLY MATERIALS

by
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ABSTRACT
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This pilot study addresses the challenges to water treatment and provision of safe domestic water supply, mostly for developing countries. In this regard, the study investigates simple, effective water treatment methods that can benefit underserved communities and improve the global progress towards achieving SDG6 and its main targets related to Clean Water and Sanitation. As such, the experimental research of this preliminary pilot study was conducted to evaluate the application of eco-friendly adsorbents and coagulants made from banana peels, eggshells, and ovalbumin protein, for water treatment. The study design analyzed three types of polluted water samples: synthetic heavy metals solution, well water samples, and E. coli stock solution. The data analysis was conducted to select the optimum factors/conditions correlated to the efficiency of the tested eco-adsorbents/coagulants: dosage, contact time, and initial pollute concentration. The response variables that were studied are (a) (R%), heavy metals removal rate (b) (TR%), turbidity removal rate (c) E. coli Reduction rate (%). The overall water quality parameters were evaluated in reference to the WHO Guidelines for Drinking Water. The statistical tools by Minitab 19 software were used to interpret the result findings related to the removal of heavy metals and turbidity.

Preliminary pilot study results showed that banana peels and eggshells eco-adsorbents/coagulants achieved desirable chromium and lead removal to levels in compliance with the WHO Guidelines for Drinking Water. The analysis of heavy metals showed that about 99.75% chromium removal and 99.95% lead removal could be attained by raw and carbonized banana peels and eggshells adsorbents. Still, the most effective eco-adsorbent/coagulant for turbidity removal was the ovalbumin protein. It reduced the turbidity levels to <5 NTU with minimal impact on the tested physio-chemical water quality parameters of color, total dissolved solids, pH, and alkalinity. Additionally, carbonized eggshells absorbents were effective in turbidity reduction at low water turbidity levels. The use of carbonized eggshells, on the other hand, exhibited the highest E. coli bacteria reduction of up to 99%. Thus, based on the findings of this preliminary pilot study, an eco-adsorbent/coagulant from carbonized eggshells and ovalbumin protein, could possibly enhance the removal of turbidity, heavy metals, and pathogenic bacteria. As such, additional studies have to be conducted with more data and modeling designs to confirm and expand the findings of this study. In addition, cost benefit analysis studies are needed to confirm the economic feasibility and applicability of the use of such eco-adsorbents/coagulants in underserved communities with limited resources, and under emergency conditions.

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CHAPTER 1

INTRODUCTION

1.1. Background of the Study

Safe drinking water, sanitation, and hygiene have been recognized as a basic need for human well-being and dignity. Access to clean water is a fundamental human right per UN Resolution 64/292 July 2010 (UN. General Assembly, 2010). Clean water, sanitation, and hygiene are essential for health and contribute to the five categories of sustainable livelihoods: human, social, financial, natural, and physical. Humans' life is central to adequate water accessibility and safe quality; the United Nations recognized it as a fundamental human right in 2002. In 2015, access to water and sanitation became a standalone sustainable development goal (SDG) since it is not only the right to essential living conditions but is crucial to humans' dignity (Chitonge et al., 2020). As such, SDG6 on "access to clean water and sanitation" has been recognized as one of the most critical sustainable development goals, the "UN's blueprint for more sustainable future for all" (Herrera, 2019). The right to water and sanitation is embedded in SDG 6 to "ensure availability and sustainable management of water and sanitation for all" by 2030. SDG 6 has eight main targets, emphasizing the need to achieve universal access to safe potable water and sanitation services equitably by 2030.

According to the 2018 SDG6 Synthesis Report, progress and improvements have reduced waterborne diseases and related water and sanitation problems (United Nations, 2018). Still, the data show that the world progress on goal 6 is still off track as 2.1 billion people still lack access to safely managed drinking water, and 3.4 million people die yearly from scarce and contaminated water sources. Moreover, at any given time, half of the world's hospital beds are occupied by patients suffering from diseases associated with a lack of access to clean water (WHO, 2020). These alarming figures show that achieving SDG 6 (6.1, 6.3, and 6.b) targets of equitable access to clean water, sanitation, and hygiene is doubtful by 2030 (WHO, 2020). That is why WASH "Water, Sanitation, and Hygiene" is currently one of the most critical public health issues to be tackled. Still, developing and low-income countries that do not provide access to water, sanitation, and hygiene for all do not recognize the importance of sustainable development (WHO, 2020).

Deficient supplies of safe drinking water and lack of access to sanitation and hygiene are the main indicative factors of poverty that are the central target of SDG1 (No Poverty). Human rights to life, freedom, liberty, education, and many others cannot be recognized when billions of people still lack access to adequate food, water, and sanitation. In addition, the increase in demand for safe drinking water is further challenged by water scarcity and climate change, especially in developing countries with increasing financing deficits to address such services. For this, safe water supplies remain a luxury in many developing countries, specifically in rural areas worldwide. Moreover, meeting the universal access targets entails changing the current unsustainable water systems to conserve the environment and reduce poverty (Herrera, 2019).

1.2. Problem Statement

Despite the improvement in providing safe drinking water supplies from governmental and non-governmental organizations, the progress remains at the level of essential services due to political, financial, and environmental challenges. Millions of people globally still lack access to safe drinking water, sanitation, hygiene due to economic, ecological, and allocation barriers (Whitley et al., 2019). In addition, today's wars and catastrophes have caused severe destruction to water and sanitation infrastructures in many areas worldwide. Moreover, COVID 19 global health crisis is a significant ongoing health and socio-economic challenge for all. WHO and other humanitarian agencies emphasize the importance of WASH services and recommend hygiene practices such as regular hand washing as necessary preventive measures against the spread of COVID19. Thus, the demand for safe drinking water and hygiene is needed more than ever and should be available to all nations (UN Water, 2020). Consequently, achieving SDG 6 targets by 2030 remains a significant challenge to meet.

This whole scenario entails widening the scope of sustainable water management approaches to conserve the environment, reduce poverty, and defeat the COVID 19 pandemic. Hence, using simple water treatment methods is optimal for enhancing access to safe water in cases of emergencies in both low and high resourced countries. Recently, studies have emphasized using environmentally friendly, simple water treatment alternatives to address public health concerns associated with commercial, widely used products. This is critical as standard water treatment products such as metal coagulants, and chemical water disinfectants have various toxic effects on humans and ecosystems if not properly controlled and administered (Krupińska, 2020).

1.3. Objectives and Research Question

1.3.1. Main Objectives

This pilot study evaluates the effectiveness of coagulants and absorbents made from organic wastes, for water treatment and their application in rural communities and under emergency conditions with minimal technical and monetary resources. The goal is to apply simple and effective water treatment methods to enhance water safety in developing countries. Consequently, the objectives of the proposed study are to:

1. Determine the efficiency of animal-based proteins as ovalbumin on removing chemical contaminants in polluted water.

2. Compare the effectiveness of various eco-adsorbents/coagulants made from organic wastes like banana peels and eggshells with the traditional coagulants such as aluminum chloride.

1.3.2. Research Question

The following research question is investigated to validate the objectives of this study: Can eco-adsorbents/coagulants from organic waste materials replace synthetic chemicals in basic water treatment without affecting the quality and safety of the treated effluents?

1.4. Study Scope

This pilot research work is centered on exploring simple treatment methods that can be applied to enhance water treatment towards achieving specified targets of SDG 6 on Clean Water and Sanitation for all by 2030. In this regard, the study investigates simple, effective water treatment methods that benefit under-resourced communities to enhance access to safe water and enhance emergency response to water pollution. This study primarily recognizes the public health deficiencies in the current water and sanitation management strategies, especially in low and middle-income countries and emergency settings.

CHAPTER 2

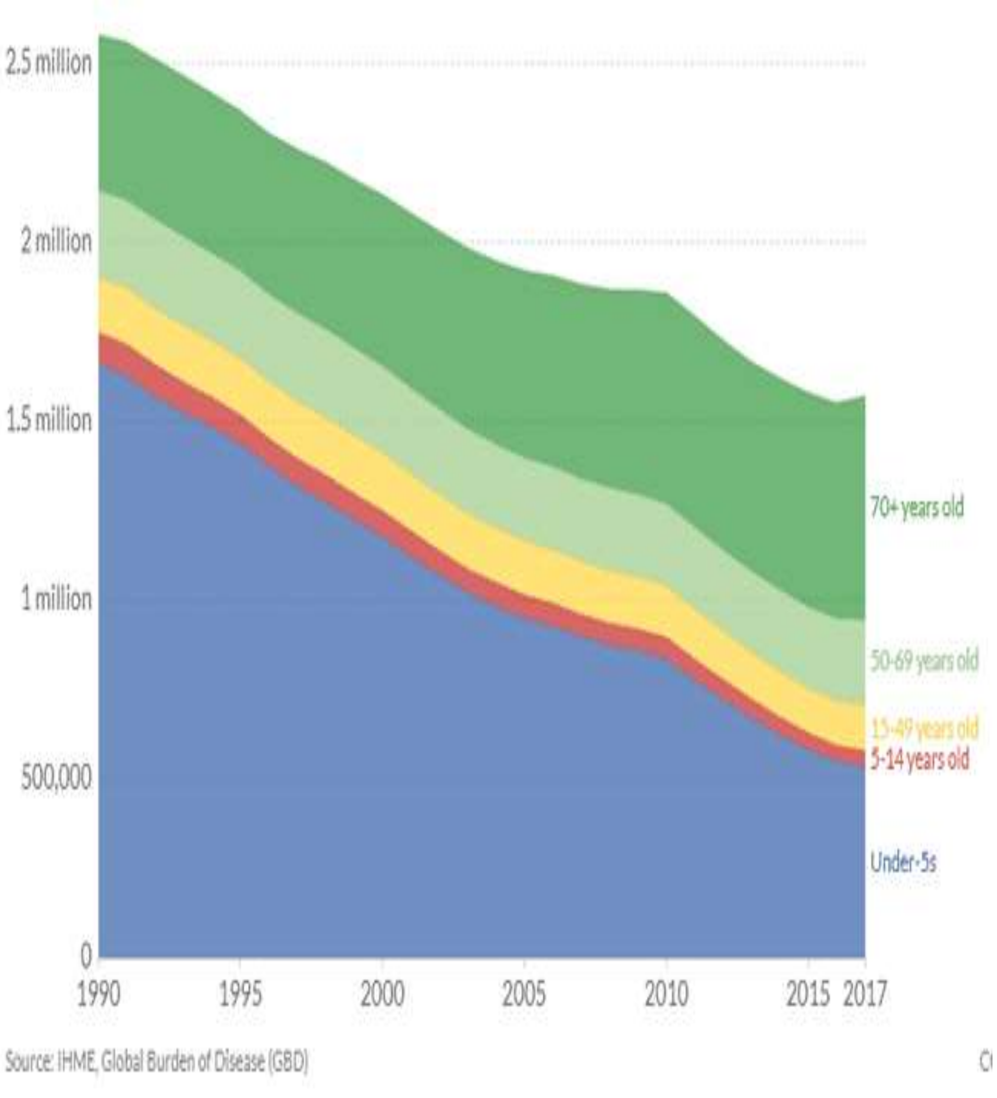
LITERATURE REVIEW

2.1. Overview of the Chapter

Chapter 2 presents the literature review on the research work under study. The review emphasizes the need to meeting SDG 6 water and sanitation targets to provide safe drinking water and adequate sanitation systems, mostly in low-income countries with minimal resources and in emergency settings. This chapter also summarizes the basic information on different water treatment methods, the historical evolution of water treatment, and the environmental concerns associated with using some conventional water treatment methods. Finally, it briefly presents the potential of using different environmentally friendly eco-adsorbents to remove specific contaminants from polluted water.

2.2. Meeting the SDG6 Challenges

According to WHO, the number of people using safe drinking water sources and improved sanitation services has increased since 1999 (WHO, 2019). According to the Global Burden of Disease World Bank statistics, the death rates from diarrheal diseases were much higher back in 1999 (WHO, 2019). However, the decline in rates of waterborne diseases was mainly in high-income countries, and still, 2.2 billion people do not have safe access to potable water and sanitation services (WHO, 2019). Death from diarrheal diseases remains one of the highest causes of death in poor and low-income countries as water and sanitation services are mostly challenged (World Bank, 2018). In 2017, 1.6 million deaths from diarrheal diseases were reported, as shown in figure 2.1 (Bernadeta, 2018). Diarrheal Diseases mainly affect children below five, making it a leading cause of death for this age group, primarily in developing countries (Bernadeta, 2018).



Source: IHME, Global Burden of Disease (GBD)

Figure 2.1: Global Deaths from Diarrheal Diseases by Age 1990 to 2017. Adapted from "Diarrheal Diseases," by B. Dadonaite, H. Ritchie, and M. Roser, 2018, Our World in Data.

Four out of five of the impacted population from the underserved communities are below the international determining poverty levels (World Bank, 2018). Women and children represent a significant percentage of this population as per the World Bank statistics 2018-2020, making them the most vulnerable to the lack of access to WASH services (World Bank, 2018). Although this access has been increasing since 2000, the percentage remains very low compared to the targets set by SDG6. Most of the population in intense rural areas, almost 80%, lack essential sanitation services, and open defecation is still practiced. People travel long distances to fetch water which is most likely not safe to drink; primarily, women and girls are the ones who travel to bring water. Further, this exposes these vulnerable groups to social and economic stresses related to loss of efficiency and productivity in work, mainly in the agricultural sector. It also raises issues relating to girls' education and gender inequality problems due to long hours spent in fetching water to meet barely the basic needs. Indeed, the lack of access to safe drinking water is affecting the livelihood assets of many under-resourced communities (WHO, 2019). Therefore, the UN has flashed the need for new strategies and plans to define the SDG 6 main challenges and accordingly, set successful interventions.

The eight targets of SDG 6, presented in figure 2.2, revolve around two primary goals. Firstly, ensuring easy access to safe drinking water and sanitation to humanity as conveyed in target 6.1. Secondly, managing the water resources in a sustainable way for environmental protection as expressed in targets 6.3 and 6.b (Chitonge et al., 2020).

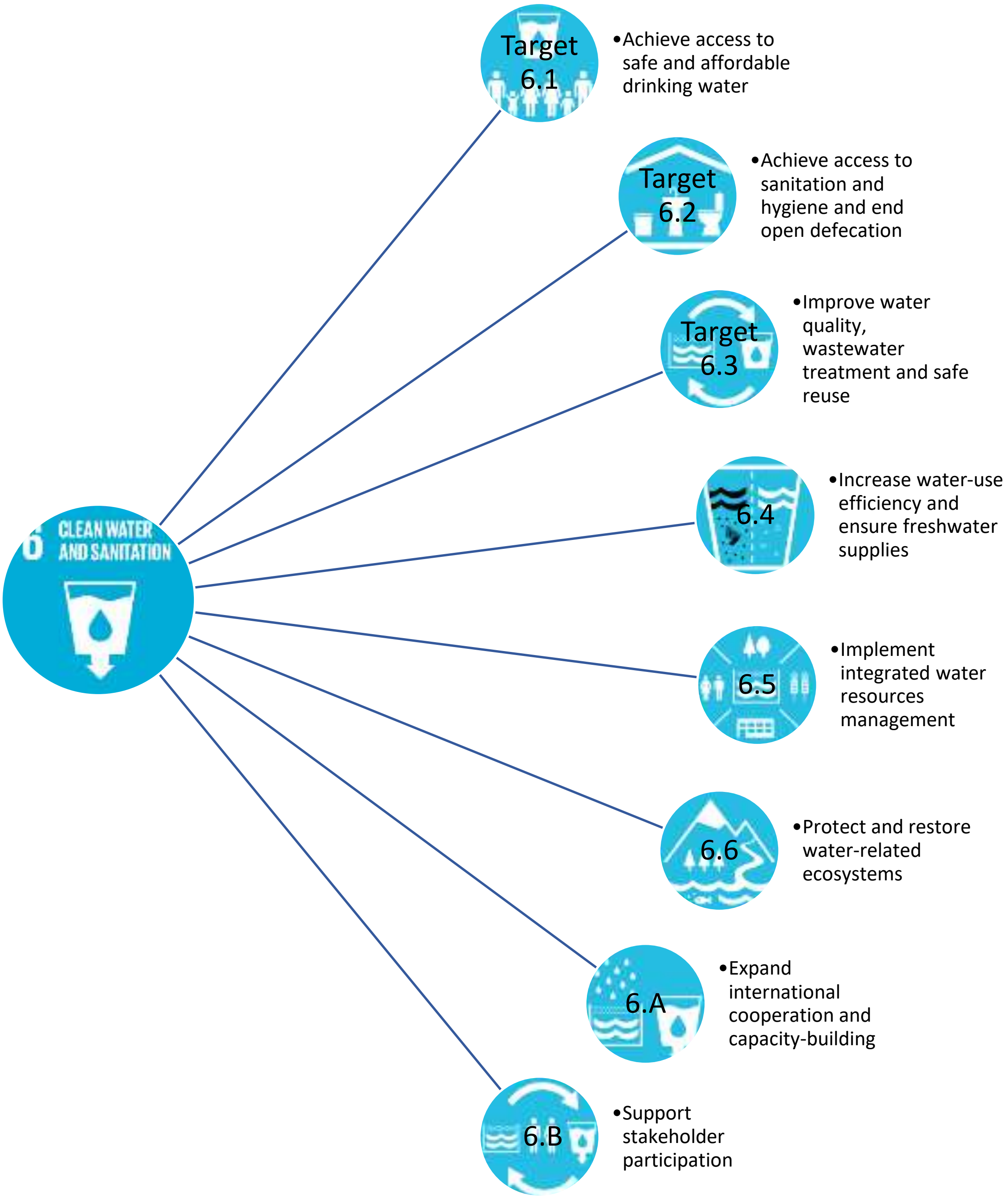


Figure 2.2: SDG 6: Targets and Indicators. Adapted from Department of Economic and Social Affairs, In United Nations, n.d, Retrieved 2021, from https://sdgs.un.org/goals/goal6. Copyright © United Nations.

The data on access to services, as presented before, show that meeting the SDG6 targets is still at the level of being realized by the public and global policies, so without immediate interventions, reaching the 2030 goal is far from being realistic. According to the 2020 WHO WASH in Health Care Report, the main challenges relate to:

1. Water scarcity and the perspective of water conservation and reuse.
2. Gaps in data collection, making it difficult to define the scale of need.
3. Lack of funding, lack of partnership opportunities, and lack of technical and human recourses.
4. Contamination of water sources and distribution systems, specifically in poor countries.
5. Climate change and the current environmental alarms and pressures directed by global warming, air pollution, water pollution, and other causes of the ecological degradation of the available natural water resources.
6. The impact of the COVID-19 pandemic on low and middle-income countries that suffer from deficient access to clean water and hygiene.

Addressing these issues requires a global recognition of the SDG 6 challenges. Therefore, there is a need for interdisciplinary coordination between all governmental and nongovernmental authorities contributing to water management at the national level. Also, this requires economic and financial support to develop and implement innovative low-cost sanitation solutions such as green economic technologies for sustainable water management services. The WASH agenda proposed needed initiatives to address SDG6 challenges, as presented below in Table 2.1 (Setty et al., 2020).

Table 2.1: Hierarchical outline of proposed WASH research agenda under Goal 6 (Setty et al, 2020)

- **Ending Open Defecation**
  - Appropriate technologies
  - Monitoring and evaluation
- **Managing Untreated Wastewater in Rural Regions**
  - Strategic Planning
  - Monitoring and Evaluation
  - Appropriate technologies
  - Economi/ sustianable/ ecological solutions
  - Reselience/ security/ climate change
- **Addressing Inequalities**
  - Gender Equality
  - Non-discrimniation/ equality among all populations.
  - Monitoring and Evaluation
- **Achieving Universal Access and Building National Capacity**
  - Public and Private sectors coordination.
  - Implementing WASH in public spaces and private institutions.
  - Global WASH access in all reomte areas.
  - National Policy and strategy/ human rights law.
- **Financing and Improving Levels of Service**
  - Equality/ non-discrimination
  - Reselience/ security/ climate change
  - Water quality/safety
  - Monitoring and Evaluation
- **Water Resources Conservation**
  - Strategic planning/ priotirization
  - sustianble/ ecological solutions
- **Strengthening Local Community Participation**
  - Reaching poorest regions
  - Equality

According to the presented outline, new development plans must prioritize the WASH needs assessments to achieve the multiple targets of SDG6 within the set timeline. These require global commitment to acknowledge and implement progressive actions, promote stakeholder involvement, community respondents, economics, and financing support. In addition, it is essential to increase the efficiency of the financial resources invested in WASH projects and find the right partnership to assist WASH researchers in facing their limitations to improve the accuracy of data acquisition and achieve proper work execution (Setty et al., 2020). Moreover, the importance of WASH has become more acknowledged in COVID-19 recommendations and guidelines. The 2020 WHO Global Progress Report on Water, Sanitation and Hygiene acknowledged the increased demand for WASH services during the COVID-19 pandemic. Additionally, it called for global responses to WASH services, especially in health care institutions and underserved communities where people are more vulnerable to the pandemic (WHO, 2020).

The MENA region is being severely affected by the water crisis conflict; it is one of the most water-stressed areas globally. This is related to the semi-arid nature of most of the Arab region due to the limited natural water resources. This created significant critical challenges related to SDG6, especially with population growth, climate change, political conflict, and the poor management of the limited available water resources (Jurdi, 2015). Among the Arab countries, the Gulf Region has high coverage of WASH services, so they reported the least number of deaths and DALYs related to unsafe water, sanitation, and hygiene. On the other hand, the other countries which represent the vast population of the Arab region suffer from major conflicts related to poor access to safe water and sanitation services. Countries like Algeria, Egypt, Iraq, Jordan, Lebanon, Libya, and Palestine are being highly challenged in sustainable water management (SDG 6). While the least developed countries like Yemen, Sudan, Somalia, and many rural regions in Egypt, are being highly threatened by unsafe water and the lack of sanitation and hygiene provision. Those countries have the highest mortality rate and DALYs from diarrheal diseases and other water-borne illnesses in the Arab region, and even globally, as the water crisis in Yemen could be one of the most disastrous among the other countries in the world. Hence, facing the challenges related to achieving the targets set by the SDG6 Agenda is one of the top priorities in the MENA region, especially for the least developed Arab countries (AFED, 2020). However, the MENA region is being way off track in terms of the SDG6 progress due to many factors such as political conflict, water scarcity, climate change, poverty, limited resources, and unsustainable man-made practices. Therefore, it is crucial to address those SDG6 severe challenges in the MENA region, which is a standalone requirement in response to the health needs specifically and contributes to environmental and socio-economic development. The Arab countries should collaborate to develop sustainable water management systems and achieve the SDG6 targets by 2030. This process of improving the water and sanitation performance in the MENA region entails the Arab countries to advance their efforts in terms of plans, policies, laws, financing, stakeholder participation, decision making, and commitment to the implementation of feasible and sustainable WASH projects (AFED, 2020; Jurdi, 2015).

2.3. Benefits of Improving WASH in Developing Countries

2.3.1. Health Benefits

Polluted water sources contain numerous microorganisms, including a wide variety of bacteria, viruses, and protozoa. Bacteria such as E-Coli, Salmonella, Fecal Coliforms, and Vibrio Cholera are prevalent microbes responsible for most waterborne illnesses, mainly diarrhea, in low-income countries. This is highly relevant in rural regions where many people still drink water directly from untreated water sources such as rivers and lakes (Pandit & Kumar, 2015). Access to safe water and hygiene is the primary preventive approach for waterborne diseases such as diarrhea. According to many case-control and cohort studies that were conducted in different low-income regions globally, the prevalence of diarrhea and other infectious diseases correlate with water quality (Wiraswati et al. 2020). The WHO recognized that more than 90% of diarrhea cases, especially for children, can be prevented by increasing access to safe drinking water and improving sanitation and hygiene (WHO, 2007). A study conducted by Wiraswati et al. generating data from 34 provinces in Indonesia, showed that the incidence of diarrheal disease was positively correlated to reduced water quality and that diarrhea victims were mostly reported in areas with the highest exposure to pollution and reduced sanitation services (Wiraswati et al. 2020). Therefore, implementing global improvement plans for water, sanitation, and hygiene systems, especially in low-income countries, will drop the burden of infectious diseases and reflect SDG 3 targets related to good health and well-being.

Additionally, the 2019 WHO Report on defeating neglected tropical diseases confirmed that simple health interventions of improving sanitation and access to safe water were associated with a significant drop in waterborne illnesses such as Neglected Tropical Diseases (NTDs) (WHO, 2015). The WHO recognized 17 NTDs, seven of which account for 90% of the disease burden, as shown in table 2.2 (Blyther, 2014).

Table 2.2: Neglected Tropical Diseases (Blyther, 2014)

Most Common NTDs (90% of all NTDs)	**Other NTDs**
Lymphatic Filariasis (Elephantiasis)	Buruli Ulcer
Onchocerciasis (River Blindness)	Chagas Disease
Schistosomiasis (Snail Fever)	Cysticercosis/Taeniasis
Soil-Transmitted Helminthiases (STH), Hookworm	Dengue
STH, Whipworm	Dracunculiasis (Guinea worm disease)
STH, Roundworm	Echinococcosis
Trachoma	Foodborne Trematode Infections

	Human African Trypanosomiasis (Sleeping Sickness)
	Leishmaniasis
	Leprosy
	Rabies
	Yaws

Such diseases are prevalent among the poorest countries where WASH services are limited as shown in figure 2.3 (WHO, 2021).

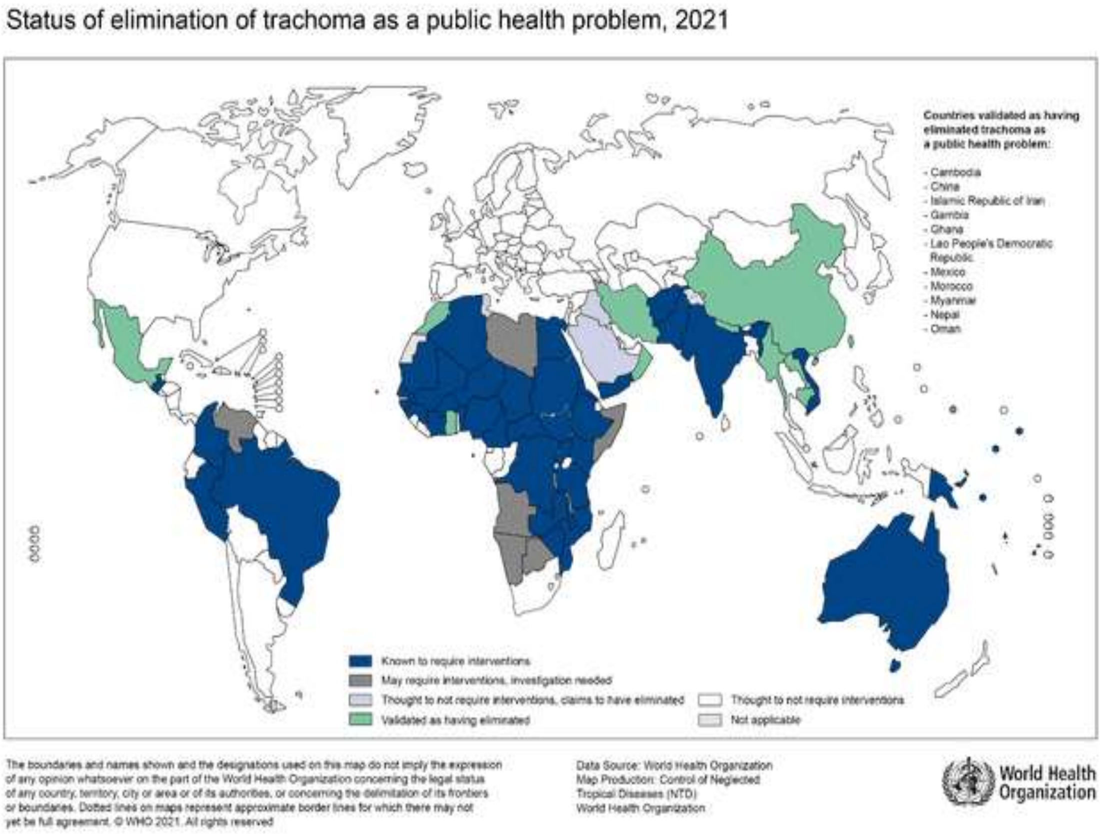


Figure 2.3: Status of elimination of trachoma as a public health problem. Adapted from THE GLOBAL HEALTH OBSERVATORY, in WHO, 2021, Retrieved, 2021, from https://www.who.int/images/default-

prevalent in the low-income regions of the world, especially in Africa. Millions of people in Africa are at risk of trachoma, one of the most common NTDs. As such, the WHO prioritized the public health interventions for the most affected countries, as shown by figure 2.3 (WHO, 2021). Those interventions mainly relate to providing safe drinking water and sanitation to achieve global progress in combating the neglected tropical diseases.

The 2020 WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene Report evaluated the worldwide progress of providing equitable WASH services, specifically among the vulnerable populations representing underserved communities. The access to simple WASH services increased from 2015 until 2020, as shown in figure 2.4. Those low-cost, simple WASH interventions, shown in table 2.3, saved the lives of millions globally.

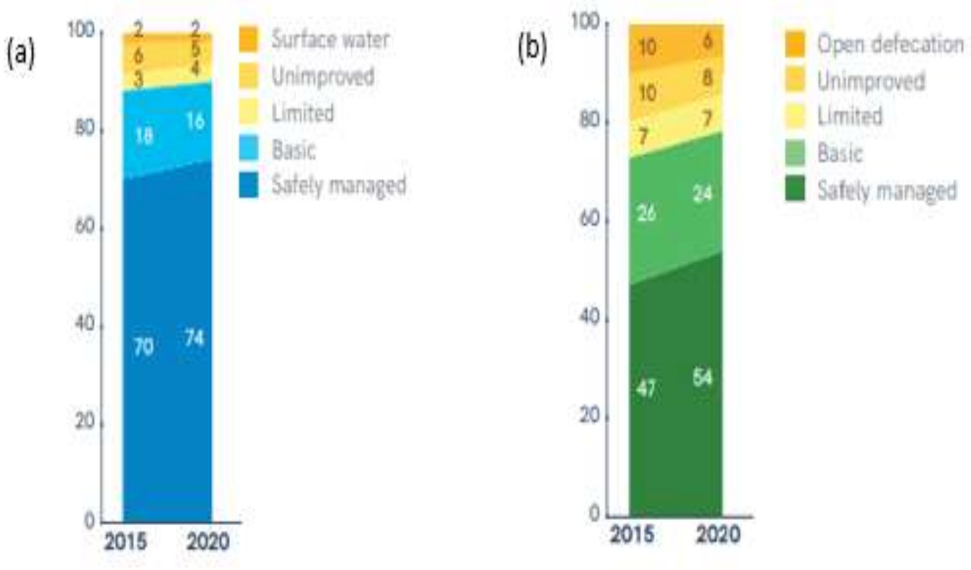


Table 2.3: Improved Facilities in Water and Sanitation (WHO, 2021)

Figure 2.4: (a). Global Drinking Water Coverage 2015-2020 (%). (b). Global Sanitation Coverage 2015-2020 (%). Adapted from “Progress on household drinking water, sanitation and hygiene 2000-2020: five years into the SDGs,” by World Health Organization, 2021.

Drinking Water	Sanitation
Piped Supplies ▪ Tap water in residence areas. ▪ Public taps ▪ Non-piped supplies ▪ Tube-wells ▪ Rainwater ▪ Monitored wells and springs ▪ Bottled drinking water ▪ Delivery of safe drinking water in tanks and drums	**Networked Sanitation** ▪ Improve toilets with flush and connecting them to sewers ▪ On-site sanitation ▪ Flush or pour-flush toilets connected to septic tanks or pits ▪ Ventilated improved pit (VIP) latrines ▪ Pit latrines with slabs ▪ Composting toilets, with twin pit latrines with slabs and container-based systems

Moreover, figure 2.4 shows that access to safe drinking water and sanitation services is increasing by year. The increase was estimated to be 48% to 81% from 2015 until 2020 (WHO, 2021). The WHO showed that those achievements resulted in significant NTDs and infectious diseases combating. In 2018, at least 1 NTD treatment from the listed in table 2.2 has reached billions of people since 2015, and 8 developing countries from Africa and Asia had eliminated at least one of the listed NTD diseases, mainly the Trachoma disease. Also, people needing treatment for Trachoma (one of the most common NTDs) dropped from 8.2 million to 2.8 million from 2007 till 2017 (WHO, 2019). Thus, achieving universal access to safe drinking water, sanitation, and hygiene is the primary preventive method for waterborne illnesses and NTDs. However, this WASH progress is still slow to achieve the 2030 goal (universal coverage for all) and, diarrhea remains a leading cause of mortality, especially for children. Moreover, 1 billion people among the most impoverished regions still suffer from NTDs chronic disabilities (WHO, 2019). Thus, global efforts by public and private institutions are needed to overcome the public and environmental health challenges acerbated by political conflict, social inequalities, economic conflict, and climate change. This entails adopting an interdisciplinary management approach that needs national and international financial support, continuous monitoring programs, and updating policy frameworks towards health inequalities (WHO, 2021).

2.3.2. Socio-Economic Benefits

As mentioned before, simple interventions to provide safe water and sanitation will prevent diarrhea diseases, especially among children. However, under-resourced communities in which most families rely on impoverished income can barely provide food and shelter. For this reason, most of the low-income communities would not prefer spending monetary investments in clean water supply and sanitation. Instead, they spend it on food and other living goods that are less costly than sanitation-initiative projects (Lal, 2014). Unfortunately, the significant direct and indirect financial and social losses associated with unsafe water supply and sanitation are unseen. Poor WASH services can lead to substantial economic expenses, including market and non-market costs such as disease treatment costs, less productivity, less economic activity such as tourism from the polluted environment, and others (Hutton & Chase, 2017). The inadequate sanitation systems in developing countries costed the global economy about US$ 222.9 billion in 2015. In 2010 the cost was US$ 182.5 billion, which indicates an increase of US$40 billion in just five years (Water Aid, 2016). The heaviest economic burden of poor sanitation is in Pacific Asia, which totals US$ 172.3 billion, almost 3/4 of the overall global cost from poor sanitation in 2015, as shown by the map (figure 2.5).

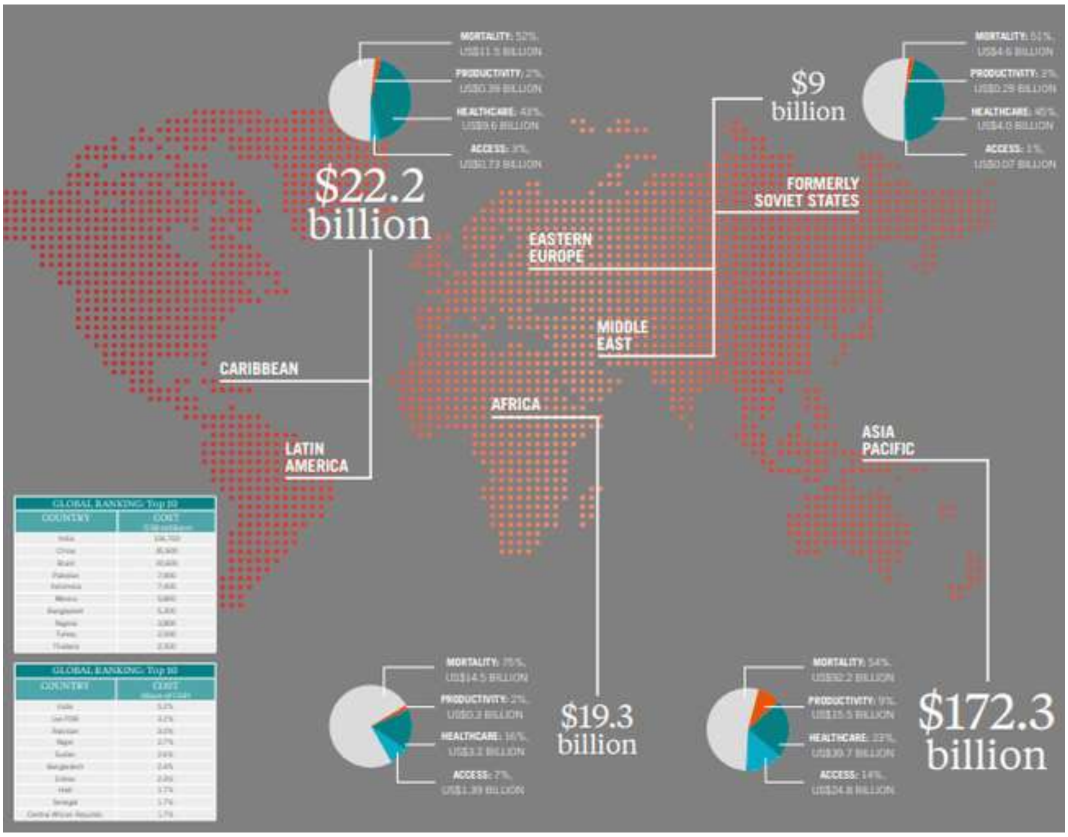
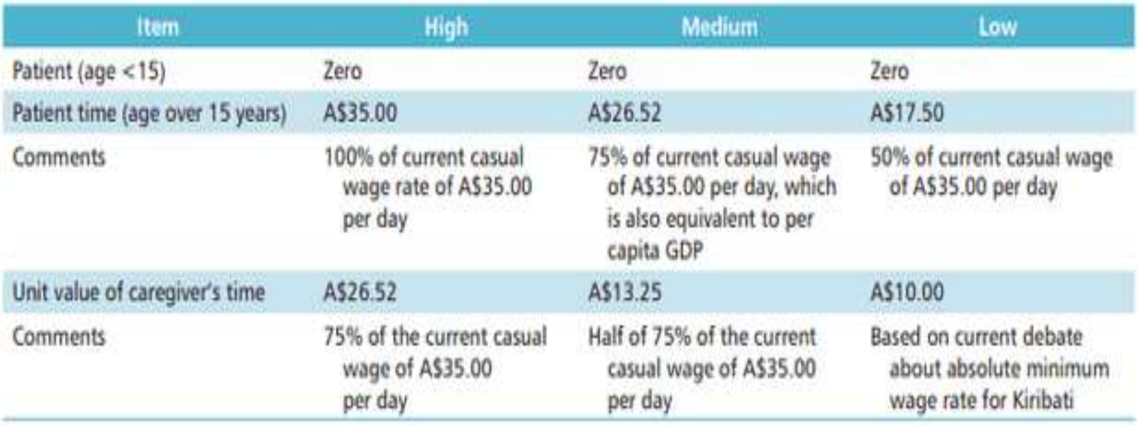


Figure 2.5: Economic Burden of Poor Sanitation. Adapted from THE TRUE COST OF POOR SANITATION, by W. Aid, 2016, https://www.publicfinanceforwash.org/sites/default/files/uploads/LIXIL-WaterAid-2016-true%20economic%20cost%20poor%20sanitation.pdf.

The financial losses include mortality, productivity, healthcare, and access to sanitation costs. Diarrhea diseases which are the leading cause of mortality due to poor sanitation and hygiene, led to economic losses of about US$122.8 billion in 2015 (Water Aid, 2016). In addition, the lack of productivity because of waterborne illnesses costed US$16.5 billion and the treatment costed US$56.6 billion. Moreover, the lack of access to toilet facilities was associated with US$27 billion in costs. Those economic losses could have been eliminated by proper water, sanitation, and hygiene systems (Water Aid, 2016). To illustrate, table 2.4 presents an example of the health treatment and loss of life costs spent in South Tawra city, Kiribati, where 1 in 5 households live at a level below the basic needs (Lal, 2014). Around US$ 3.7-7.3 million have been spent annually to treat waterborne illnesses in South Tarawa. The expenditure was mainly on medicines, hospitality, transportation that would have been avoided by providing proper water systems and sanitation services (Lal, 2014). This further shows the lack of awareness in developing countries about the indirect costs of medication spent on diseases' treatment and other issues due to deficient water supply and sanitation services.

Table 2.4: Opportunity Cost Scenarios to Estimate Loss in Economic Productivity Due to Water-Borne Illnesses and the Value of Caregiver's Time. Adapted from "Economic Costs of Inadequate Water and Sanitation: South Tarawa,Kiribati" by L. Padma, 2014,



Item	High	Medium	Low
Patient (age <15)	Zero	Zero	Zero
Patient time (age over 15 years)	A$35.00	A$26.52	A$17.50
Comments	100% of current casual wage rate of A$35.00 per day	75% of current casual wage of A$35.00 per day, which is also equivalent to per capita GDP	50% of current casual wage of A$35.00 per day
Unit value of caregiver's time	A$26.52	A$13.25	A$10.00
Comments	75% of the current casual wage of A$35.00 per day	Half of 75% of the current casual wage of A$35.00 per day	Based on current debate about absolute minimum wage rate for Kiribati

Despite the lack of awareness of the economic burden of poor sanitation by developing communities, the socio-economic benefits of improving WASH services have been recognized since 1992. The Water and Health Protocol have implicitly confirmed the socio-economic benefits of providing people with WASH services to the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes, which came into force in 2005 (Noga & Wolbring, 2012). The protocol clearly illustrated that equitable access to water and sanitation is necessary to eliminate social exclusion (Noga & Wolbring, 2012). In addition, the UN Statement on the right to sanitation (45th session, E/C.12/2010/1) clearly emphasized that equitable access to sanitation is a critical factor in eliminating all forms of social discrimination (Noga & Wolbring, 2012).

Further, investing in WASH projects is associated with main social benefits such as educational improvement. According to the 2018 UN News, children's education in low-income communities is threatened by the lack of clean water and toilets (UN, 2018). Many children in rural regions do not attend schools because of diarrheal diseases caused by the limited access to WASH. Girls are more vulnerable in the rural areas because of the considerable time they spend daily bringing water to their families, which also contributes to economic losses, as presented before (UN-Water, n.d). According to the World Bank (2015), improving WASH services can have a cost but results in significant social benefits. Table 2.5 illustrates the yearly cost benefits for primary interventions such as eliminating open defecation, universal access to drinking water at home, and universal access to basic sanitation at home, achieving universal WASH coverage (100%). It can be inferred that the benefits from investments in WASH interventions exceed the cost of implementing those interventions. This includes mainly: financial savings related to reduced medical costs for disease treatment, monetary savings on improving productivity, and reducing mortality which is reflected by the per capita GDP (Hutton, G., & Whittington, 2015).

Table 2.5: Annual costs and benefits to meet and sustain universal access (100% coverage), focusing on the projected unserved population in 2015 (US$ B) (Hutton, G., & Whittington, 2015)

Intervention	Daily Value	3% Discount			5% Discount		
		Benefit	Cost	BCR	Benefit	Cost	BCR
Eliminate open defecation (rural only)	1000	81	14	5.8	73	12	6
	500	99	14	7.1	87	12	7.3
Universal access to basic drinking water at home	1000	50	15	3.3	40	13	3.3
	500	66	15	4.4	54	13	4.2
Universal access to basic sanitation at home	1000	94	33	2.9	81	28	2.9
	500	107	33	3.3	90	28	3.2

BCR is the amount of times the benefits exceeds the cost of intervention

2.3.3. Environmental Benefits

Water and Sanitation are also vital components to the environment, and together they constitute the main drivers of the Millennium Development Goals. Improper environmental management leads to the unsuccessful implementation of WASH programs water and wastewater treatment, and sustainable management of water resources are principal factors to WASH programs (Motala et al., 2015). That's why every dollar spent on water and sanitation projects contributes to environmental protection, which is achieved by implementing sustainable water management programs and providing sanitation services that include economically feasible wastewater treatment systems and appropriate waste management solutions (Hutton, G., & Whittington, 2015). However, despite the improvements made in enhancing environmental performance by increasing WASH access, many regions in low-income countries are still being threatened with severe environmental concerns. Those are the vulnerable areas of environmental degradation where the people's livelihoods are severely affected (Motala et al., 2015).

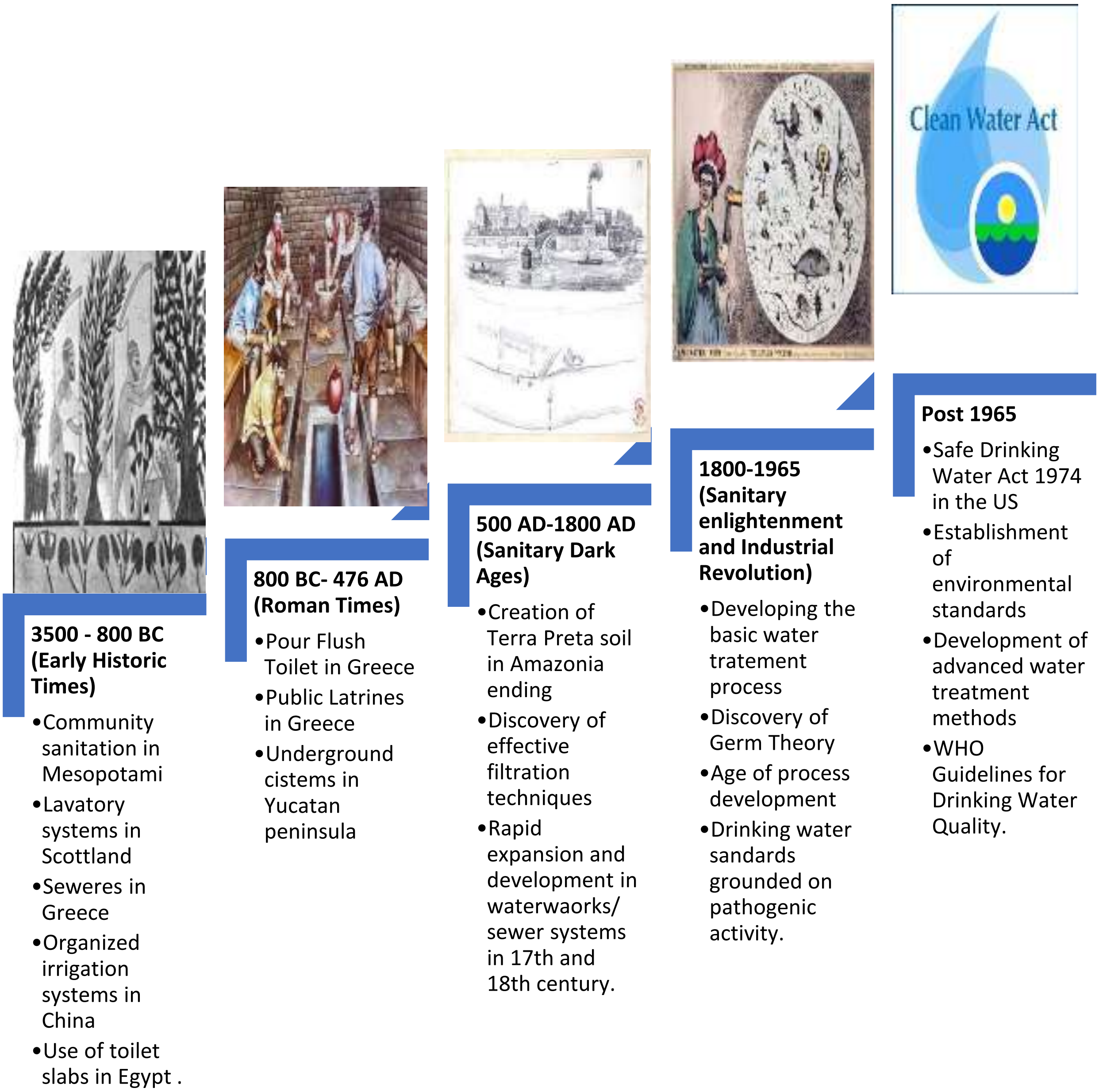
The lack of proper sanitation infrastructure and sustainable water and waste management systems have created millions of slums in the urban regions of low-income countries, causing severe environmental concerns such as air and water pollution. In populated urban areas such as India, rapid industrialization and unsustainable agriculture are widely practiced, intensifying the water contamination that affects the primary sources of drinking water and the domestic water supply (Hutton & Chase, 2017). In addition, most of the generated wastewater from domestic and industrial sectors is disposed of untreated, causing severe pollution of water bodies and related ecosystems. This leads to adverse environmental and health effects related to the release of chemicals and pollutants present in wastewater to the ecosystems. The groundwater, riverbeds, and wetlands have been threatened with the increase in persistent chemicals and biological contaminants, which is associated with adverse health effects related to the accumulation of those toxic pollutants in aquatic organisms, soil, and the surrounding ecosystems which enter the food chain to the humans (Edokpayi et al., 2017).

In addition, global warming is worsening water stress and scarcity, especially in areas limited with water resources. Climate change is representing a significant challenge for the WASH sector, especially in areas with higher risks of floods and tropical regions that are sensitive to the spread of diseases. This increases the urge to implement sustainable WASH programs that promote environmental management systems for the sustainable supply of safe water. Those programs should be integrated with proper wastewater management and sustainable WASH infrastructures, such as implementing strategies for the safe disposal of sewage and wastes without harming the environment. Those sustainable WASH interventions would reduce the environmental impacts and help in bringing up the resilience of climate change (WASH, 2018).

2.4. Water Treatment and Management

2.4.1. History of Water Treatment

Historical facts show that water and sanitation management is part of the old humans' behaviors and practices explained as part of human's originality. Sanitation and hygiene began as a rational concept as humans practiced it since they felt its right. Various descriptions were related to norms, religions, and culture, and sometimes sanitation was related to naturalism. Thus, the concept of understanding water quality was not very common in the past but existed symbolically. Hygiene practices existed in historical cultures, social norms, science and were illustrated as a basic code in all religions. The ancient Greek medical writers and philosophers recognized the importance of "pure" water to public health (IWA, 2008). Therefore, hygiene and sanitation are old concepts that will remain vital to human welfare. Great nations and empires have settled near the most important rivers and abundant natural water resources (UNESCO, 2011). Hence, the provision of safe drinking water and sanitation is not a modern phenomenon, and water management has evolved through a historical progression with time, as presented in figure 2.6 (Bond et al., 2013). Figure 2.6 shows that improving water quality started by enhancing water appearance and taste. The concept of water and sanitation evolved, and water management systems became a significant part of the ancient civilizations.



3500 - 800 BC (Early Historic Times)

- Community sanitation in Mesopotami
- Lavatory systems in Scottland
- Seweres in Greece
- Organized irrigation systems in China
- Use of toilet slabs in Egypt .

800 BC- 476 AD (Roman Times)

- Pour Flush Toilet in Greece
- Public Latrines in Greece
- Underground cistems in Yucatan peninsula

500 AD-1800 AD (Sanitary Dark Ages)

- Creation of Terra Preta soil in Amazonia ending
- Discovery of effective filtration techniques
- Rapid expansion and development in waterwaorks/ sewer systems in 17th and 18th century.

1800-1965 (Sanitary enlightenment and Industrial Revolution)

- Developing the basic water tratement process
- Discovery of Germ Theory
- Age of process development
- Drinking water sandards grounded on pathogenic activity.

Post 1965

- Safe Drinking Water Act 1974 in the US
- Establishment of environmental standards
- Development of advanced water treatment methods
- WHO Guidelines for Drinking Water Quality.

Figure 2.6: WASH Practices Historical Evolution Timeline (Bond et al, 2013)

According to Jadhav (2014), references to water treatment methods have been documented by the ancient Greeks, as early as 4000 BC. Moreover, ancient Egyptians in 1500 BC discovered coagulation and flocculation techniques by using different clays and chemicals such as earth’s Alum. Those elementary materials promoted the grouping of tiny, suspended particles into larger flocs that were settled quickly from water

(Jadhav, 2014). In addition, different water “purification” methods by natural substances existed, including using various kinds of herbs, algae, and stones as quartz crystal and others. Moreover, exposure to sunlight and boiling were standard methods of water disinfection since ancient times (Jadhav, 2014). The discovery of invisible water contaminants started in the mid of 1800s where scientists began to link waterborne diseases to microbial organisms (EPA, 2000). In the 1700s, effective filtration techniques for water clarification were established. However, measuring the degree of clarity to the extent that it is not visible by the eye was not yet discovered.

During the late nineteenth century, scientists focused on diseases caused by pathogens (microbes) leading to waterborne diseases such as diarrhea, cholera, malaria, hepatitis, and other fevers that were primarily fatal due to inadequate medical treatment. Accordingly, scientists proposed many theories relating germs to diseases at that time. One of the most important and currently accepted scientific theories is "The Germ Theory," that Louis Pasteur first established in the late 1880s (EPA, 2000). During the early 20th century, disinfection by chlorination killed most "germs" in drinking water sources, reducing waterborne diseases. Post the 1960s; public health concerns started to acknowledge the chemical contamination of water. It was due to rapid industrialization and urbanization (EPA, 2000). Then, increased global awareness of anthropogenic water pollution led to the development of environmental health legislation. The "Safe Drinking Water Act (SDWA) 1974" by the USA Environmental Protection Agency (EPA) set standards for naturally occurring or artificial contaminants in drinking water (EPA, 2000). Concurrently, WHO issued four editions of the Guidelines for Drinking Water Quality (GDWQ) (1983–1984, 1993–1997, 2004, and 2011) as a follow up to the WHO Guidelines for Drinking Water published in 1957 (WHO, 2011). As such, the historical evolution of civilizations led to various water and sanitation management approaches. Thus, understanding the historical frame is very helpful in brainstorming the water and sanitation problems. In addition, it helps to identify the main gaps and come up with powerful means of water and sanitation enhancements. Looking at the current situation, in most rural areas in developing countries, basic practices of thousands of years ago are not even implemented in an era where technology is growing unpredictably.

2.4.2. Development of Water and Wastewater Treatment Methods

As presented in the previous section, the history of water treatment represents evolutionary events that have shaped today's water treatment methods and systems. Figure 2.7 shows a sequential development of the different techniques and practices in water and wastewater treatment. The major developments in water and wastewater treatment have been witnessed since the mid of the 19th century.

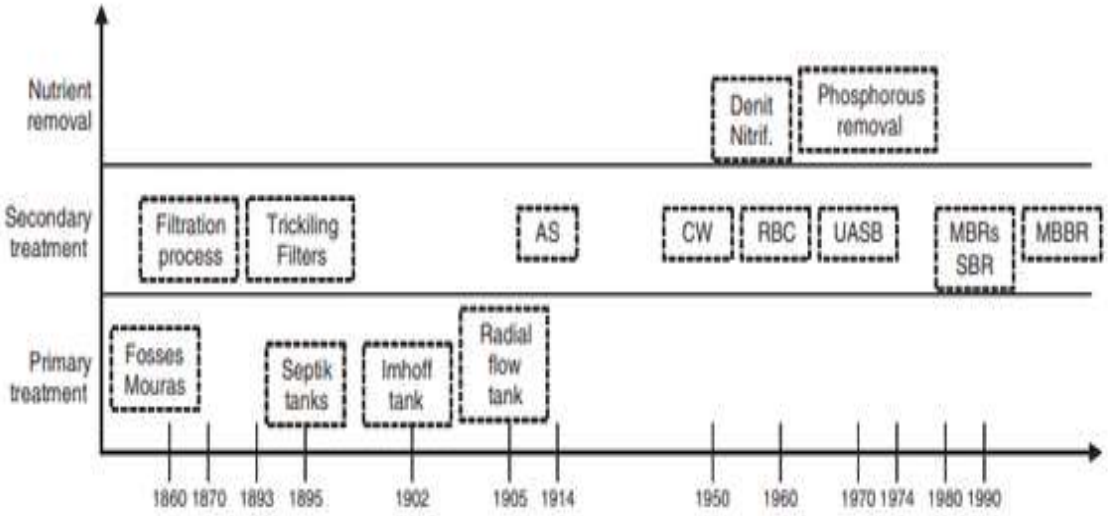


Figure 2.7: Evolution of wastewater treatment. Adapted from "Wastewater management through the ages: A history of mankind," by G. Lofrano, and J. Brown, 2010, Science of the Total Environment, 408(22).

According to Crittenden et al. (2012), the most common conventional water treatment methods applied today include coagulation-flocculation, sedimentation and filtration, and disinfection. Sedimentation and filtration are standard methods of mechanical water treatment (physical water treatment) that allow the suspended particles in water to settle under the effect of gravity. The coagulation process is one of the most common conventional water treatment techniques. Metal coagulant polymers, mainly aluminum and iron coagulants, are added to untreated water effluents before the mechanical separation. After that, sedimentation or filtration stabilizes the suspending particles and enhances turbidity removal, removing organic matter and some types of microorganisms. The disinfection process destroys all pathogenic organisms present in water and is usually one of the last steps in this conventional drinking water treatment (Crittenden et al., 2012). Moreover, nowadays due to industrialization huge amounts of heavy metals are being discharged to the environment mainly by the wastewater that have been contaminated from pesticides, fertilizers, dyes, pharmaceutical residues, and others (Renu et al, 2017). The most conventional methods that have been used for the removal of heavy metals contamination includes chemical precipitation, ion exchange, membrane separation, chemical oxidation, and reverse osmosis (Tripathi & Ranjan, 2015).

Advanced water and wastewater treatment, on the other hand, constitute physical, chemical, and biological systems that comprehensively remove insoluble and soluble pollutants, and hazardous contaminants such as the heavy metals from the untreated effluents (Crini, & Lichtfouse, 2019). Those advanced water and wastewater treatment methods include technologies such as the membrane processes, which include Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), Forward Osmosis (FO), and Reverse Osmosis (RO). In addition, the Membrane Bioreactor (MBR) and Membrane Bed Biofilm Reactor (MBBR) are among the most advanced water and wastewater treatment methods. These methods combine biological treatment to obtain optimum BOD and COD removal rates. Hence, numerous processes for advanced water and wastewater treatment have been developed over the last 30 years to cope with the growing demand for water (Crini, & Lichtfouse, 2019). However, those advanced technologies have been perceived with financial and environmental challenges for being very costly, demanding high energy input, and disrupting the environment without proper energy recovery (Sancho et al., 2015). This is a vital challenge requiring effective economic and risk management frameworks to successfully implement economically feasible water and sanitation projects to achieve SDG6 goals and targets.

2.4.3. Water Treatment Challenges

Unsafe water remains a key challenge in developing countries arising from poor planning and implementation of water and wastewater treatment (Sancho et al., 2015). Those challenges relate to a lack of human, technical, and monetary resources. The use of advanced water and wastewater treatment methods such as desalination processes and reverse osmosis effectively removes all undesirable contaminants. Still, those technologies require high operational and maintenance costs, making them economically not feasible in many developing countries (Kausley et al., 2018). However, the cost of no action on water and sanitation projects remains one of the central challenges for SDG6. Thus, the economic assessment of feasible WASH projects remains complex since it depends on an interdisciplinary management approach combining social, political, and environmental aspects which do not have a specific market price. Sustainable WASH programs to achieve SDG6 should be an integral component in integrated water resources management (IWRM). Moreover, the implementation of WASH should be continuously monitored and sustained (Carrard & Willetts, 2017).

Sustainable WASH programs to achieve SDG6 should be an integral component in integrated water resources management (IWRM). Moreover, the implementation of WASH should be continuously monitored and sustained. (Carrard & Willetts, 2017). Additionally, the benefits of implementing WASH programs in developing countries should be weighed and assessed by a suitable financial approach to have a proper economic justification for the feasibility of its application, as shown in figure 2.8. Accordingly, WASH projects and programs in developing countries face difficulty calculating implementation's associated costs and benefits (Sancho et al., 2015). Addressing this challenge shall be followed by extensive efforts and research on efficient cost-analysis approaches and methodologies to promote techno-economically feasible WASH projects in developing countries (Sancho et al., 2015). This should be done in a holistic analysis manner, including health, environmental, social, and economic aspects (Sancho et al., 2015).

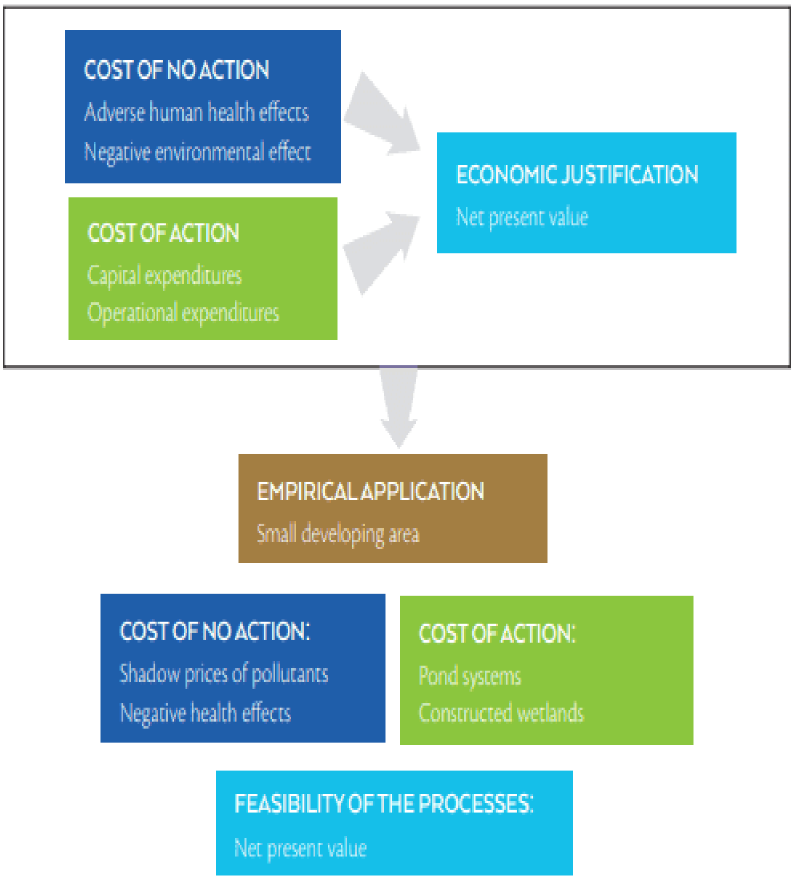
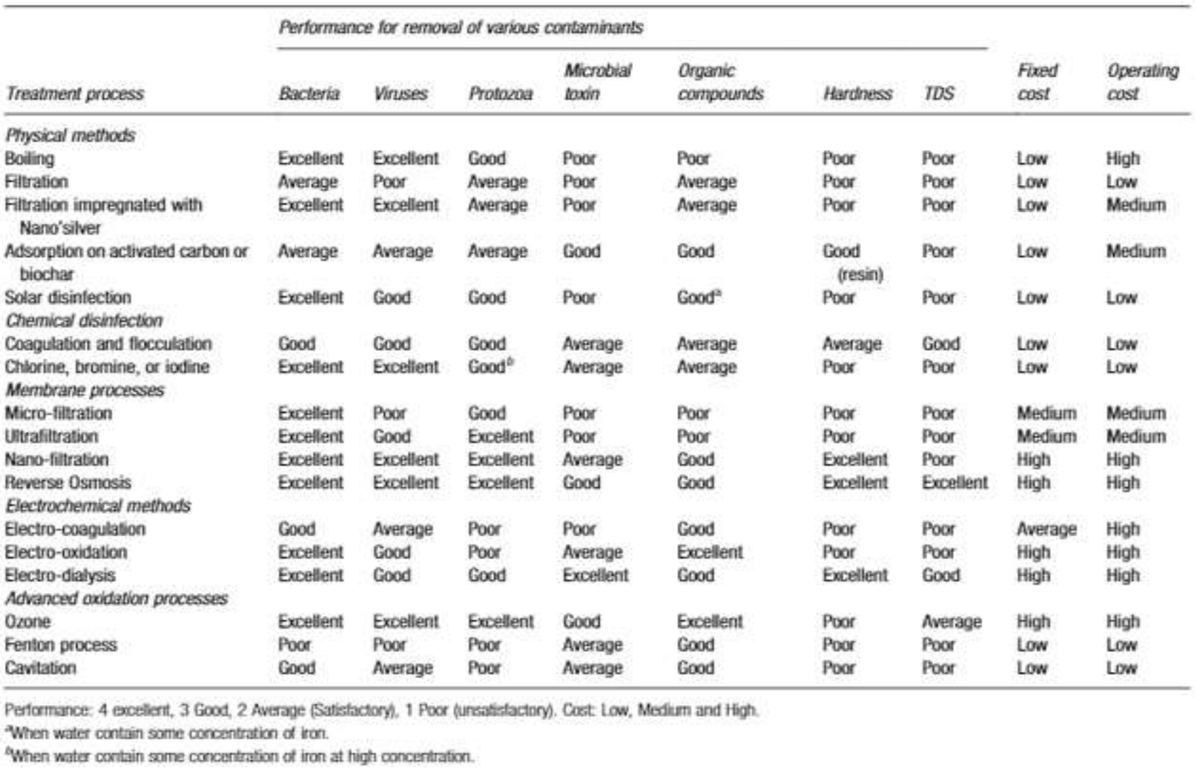


Figure 2.8: Schematic of the approach followed to assess the cost of action and the cost of no action for wastewater management. Adapted from Economic valuation of wastewater: the cost of action and the cost of no action, by H. Sancho et al., 2015, United Nations Environment Programme (UNEP).

2.4.4. Simple Drinking Water Treatment Approaches

Developing effective, economical methods to improve water quality in developing countries is one of the most dynamic research fields in this period (Crini, & Lichtfouse, 2019). Household water treatment can be a cost-effective method to improve millions of vulnerable populations (WHO, 2007). The WHO proposed household water treatment (HWT), referred to as point-of-use water management (POU), including filtration, coagulation, and flocculation chlorination, boiling, and solar disinfection. The point-of-use (POU) or household water treatment (HWT) methods are one of the most recommended drinking water treatment solutions in developing countries, especially in rural regions, due to its technological simplicity, low cost, low maintenance, and its capability of providing safe drinking water at an individual level (Pooi et al., 2018). For achieving the target of adequate provision of safe drinking water in developing countries, it is essential to study the overall performance of the proposed HWT technologies. The proposed water treatment method shall effectively eliminate the health risks associated with the unwanted drinking water contaminants, be economically feasible for the long term, and be sustainable in rural environments (Kausley et al., 2018). Table 2.6 compares different water treatment techniques regarding their technical-economic practicability in developing countries and evaluates their associated water treatment performance.

Table 2.6: Techno-economic feasibility of various treatment processes for purification of drinking water. Adapted from “Clean Water for Developing Countries: Feasibility of Different Treatment Solutions,” by S. Kausley et al., 2018, Encyclopedia of Environmental Health.



	Performance for removal of various contaminants								
Treatment process	*Bacteria*	*Viruses*	*Protozoa*	*Microbial toxin*	*Organic compounds*	*Hardness*	*TDS*	*Fixed cost*	*Operating cost*
Physical methods									
Boiling	Excellent	Excellent	Good	Poor	Poor	Poor	Poor	Low	High
Filtration	Average	Poor	Average	Poor	Average	Poor	Poor	Low	Low
Filtration impregnated with Nano’silver	Excellent	Excellent	Average	Poor	Average	Poor	Poor	Low	Medium
Adsorption on activated carbon or biochar	Average	Average	Average	Good	Good	Good (resin)	Poor	Low	Medium
Solar disinfection	Excellent	Good	Good	Poor	Good[a]	Poor	Poor	Low	Low
Chemical disinfection									
Coagulation and flocculation	Good	Good	Good	Average	Average	Average	Good	Low	Low
Chlorine, bromine, or iodine	Excellent	Excellent	Good[b]	Average	Average	Poor	Poor	Low	Low
Membrane processes									
Micro-filtration	Excellent	Poor	Good	Poor	Poor	Poor	Poor	Medium	Medium
Ultrafiltration	Excellent	Good	Excellent	Poor	Poor	Poor	Poor	Medium	Medium
Nano-filtration	Excellent	Excellent	Excellent	Average	Good	Excellent	Poor	High	High
Reverse Osmosis	Excellent	Excellent	Excellent	Good	Good	Excellent	Excellent	High	High
Electrochemical methods									
Electro-coagulation	Good	Average	Poor	Poor	Good	Poor	Poor	Average	High
Electro-oxidation	Excellent	Good	Poor	Average	Excellent	Poor	Poor	High	High
Electro-dialysis	Excellent	Good	Good	Excellent	Good	Excellent	Good	High	High
Advanced oxidation processes									
Ozone	Excellent	Excellent	Excellent	Good	Excellent	Poor	Average	High	High
Fenton process	Poor	Poor	Poor	Average	Good	Poor	Poor	Low	Low
Cavitation	Good	Average	Poor	Average	Good	Poor	Poor	Low	Low

Performance: 4 excellent, 3 Good, 2 Average (Satisfactory), 1 Poor (unsatisfactory). Cost: Low, Medium and High.

[a] When water contain some concentration of iron.

[b] When water contain some concentration of iron at high concentration.

According to the data presented in table 2.6, it can be inferred that coagulation and flocculation combined and disinfection methods are associated with low fixed and operating costs. The coagulation and flocculation showed good performance in removing microorganisms and total dissolved solids from water. The disinfection methods showed excellent performance in removing microorganisms from water but a poor performance in removing total dissolved solids. Thus, it can be concluded from Table 2.6 that producing safe drinking water at the household level can be achieved by techno-economic water treatment methods that include coagulation, filtration, and disinfection. Those can represent essential methods to handle the water quality crisis in underserved communities (Pandit & Kumar, 2015). In addition, as stated earlier the anthropogenic water pollution is a serious problem nowadays, and this is even more challenging in the developing countries due to the unsustainable industrial and agricultural practices which is leading to the discharge of toxic heavy metals to the water resources and the surrounding ecosystem. Therefore, it is essential to corporate a low-cost method for heavy metals reduction and removal with the proposed techno-economic drinking water treatment methods. The adsorption technique by using adsorbents such as the activated carbon, have been proposed as a low-cost and efficient process for heavy metals removal over the conventional methods (Renu et al, 2017).

2.4.4.1. Filtration Techniques

Advanced filtration technologies such as membrane filtration and reverse osmosis (RO) became among the broadest water treatment technologies due to their high effectiveness in water purification. Still, the rural areas, which represent a large proportion of the low and middle-income countries, cannot afford the implementation of those expensive technologies. Therefore, simple and traditional household filtration techniques were adopted in many rural regions. Those methods filter out visible suspended solids and some undissolved impurities from the water, but alone they can't deliver desirable drinking water per WHO drinking water guidelines. However, the corporation of the traditional filtration methods with further treatment by adding coagulant aids and disinfectants could yield safe water for drinking (Vigneswaran & Sundaravadivel, 2009). There are different types of traditional household filtration methods; some common ones are filtration through winnowing sieve, filtration through cloth, and filtration through clay vessels. The winnowing sieve filter can effectively remove some of the physical impurities in water and coarse particles; those impurities are filtered by passing the contaminated water through the sieve filter. The filtration through cloth includes using thin cotton or any clothing item with suitable pore size. The raw water is passed through the cloth item, which can remove impurities such as small debris particles, insects, dust and mud particles, and some suspended particles but in a limited manner (Vigneswaran & Sundaravadivel, 2009). However, the filtration done by these two methods is not suitable for high turbid water, unlike the filtration through clay vessels. The clay vessels should have a suitable pore size to filter the high turbid water. The turbid water is allowed to settle down in the clay jar, and then the water will drop through the pores on the clay jar's pores. Finally, this water is collected in a vessel (such as a clay pot) placed at the bottom of the porous clay jar (Vigneswaran & Sundaravadivel, 2009). Other improved filtration methods, such as granular media filtration and ceramic water filters, can be techno-economically feasible and easy to apply in rural regions. The bio-sand filter, one of the most popular granular media filters, has been proposed by many water experts as a household treatment method for people with limited access to safe water in rural regions. It is easy to use and has a low maintenance cost; the sand filter can be simply placed in a plastic or concrete container at the household level. The bio-sand filter is applicable for high turbid waters, and it can obtain more than 90% bacterial reduction (Zin et al., 2018). The ceramic water filters were also proposed for point-of-use water treatment in rural regions. The ceramic water filters represent a low-cost and effective treatment method for raw water that contains debris materials, dirt, and bacteria. It is composed of a ceramic material with tiny pores placed on top of a vessel or container. The vessel material is usually made from clay, plastic, or ceramic. The ceramic filters were proved one of the most effective, low-cost, and sustainable household treatment methods in reducing diarrhea and other waterborne diseases due to their high effectiveness in reducing bacterial microorganisms. In addition, some studies showed that ceramic filters could be used for longer-term by the consumers than the bio-sand filters (Zin et al., 2018). As such, inexpensive drinking water treatment techniques have been proposed and used in rural regions, but further development is still needed to accomplish the SDG6 goals.

2.4.4.2. Chemical Coagulation and Flocculation

As presented before, coagulation and flocculation compromise the addition of coagulant and flocculants chemicals with opposite charges of those suspended particles in water or wastewater to destabilize the charged particles, which cause them to stick together, forming flocs with the desired size to be easily removed from water (Prakash et al., 2014). Coagulation-flocculation can be used as means of treatment to remove some of the common impurities from water, mainly turbidity and small suspended solids. In addition, this process can enhance the removal of specific heavy metal ions such as iron. Aluminum and iron-based coagulants have been globally used for community drinking water treatment purposes. Aluminum Sulphate and Iron Sulphates are considered the most used chemical coagulants, especially for community-scale water treatment purposes, due to their lower cost than other chemical coagulants (Pandit & Kumar, 2015). Other chemical coagulants are aluminum chloride, sodium aluminate, ferric chloride, ferrous sulfate, and ferric chloride sulfate (Bratby, 2016). However, many developing countries cannot afford the overall cost of traditional coagulants. Thus, natural coagulants, which are less-costly alternatives, have been suggested for household water treatment (HWT), especially in rural regions. In low-income communities, the cost of the coagulant is one of the essential factors in determining its practicality and efficiency for the long term (Vara, 2012).

Table 2.7 lists different coagulants used for drinking water treatment and their associated advantages and disadvantages (Bartram, 2007).

Table 2.7: Coagulants for Water Treatment and their Advantages, Disadvantage and Costs (Bartram, 2007)

Coagulant	**Community/ Household Use**	**Advantages**	**Disadvantages**	**Cost**
Alum (aluminum sulfate, alum chloride, etc)	Yes/ moderate	Simple technology, especially for community scale applications	Technical difficulties in optimization. Can be associated with chronic toxic effects to human health and the environment.	Moderate
Iron (ferric chloride or sulfate)	Yes/ rare	Same as Alum	Same as Alum	Moderate
Lime	Yes/ rare-moderate	Same as Alum	Same as Alum. pH control problem	Moderate to High
Synthetic organic polymers	Yes/ no-rare	Improve coagulation with Alum and iron coagulants	Same as Alum. Technical difficulties with dosing and equipment.	High

Natural polymers from seeds, beans, agricultural wastes, etc.	Rare/ yes (have been applied in some low-income countries	Effective, abundant, eco-friendly, and is not associated with eco-toxic concerns to humans and ecosystems.	Not widely used so it requires training and skills. Cultural acceptance	Low

It can be concluded from Table 2.7 that different factors determine the right choice of the coagulant polymer to be used, such as its water treatment outcomes effectiveness and its cost. Table 2.7 shows that natural polymers can represent a practical choice for underserved communities. Still, it is crucial to study the optimum conditions which influence the efficiency of the selected coagulant polymer. The factors which affect the coagulation activity in water compromise several factors, such as the: coagulant polymer dose, polymer molecular weight, the charge of the functional group, properties of pollutants present in water, and the physio-chemical properties of the water source at the household level (Bratby, 2016).

2.4.4.3. Simple Disinfection Methods

The current drinking water disinfection practices eliminated all pathogenic microorganisms responsible for the main waterborne illnesses. The most used chemical disinfectant is chlorine (CDC, 2012). Other disinfectants, such as bromine, iodine, alcohols, hydrogen peroxide, are also used. Still, the mentioned chemical disinfectants can react with the organic compounds present in water, so EPA recommended removing the organic matter before adding those (Sharma & Bhattacharya, 2017). Additionally, physical disinfection methods include UV irradiation, radiation, sonic or hydrodynamic pressure. Also, the oldest and simplest disinfection methods, boiling and solar disinfection are still practiced (Crittenden et al., 2012). Disinfection is an essential requirement for potable water treatment purposes, and its biocidal efficiency is strongly dependent and interrelated with other treatment techniques. In other words, disinfection should kill all pathogenic microorganisms (CDC, 2012).

The point-of-use disinfection techniques can be an economical choice in underserved communities. Implementing low-cost and energy feasible disinfection methods is critical for the vulnerable communities in developing countries where most people still rely on drinking water sources contaminated with various pathogens (WHO, 2019). The Chronic Diseases Center (CDC) suggested using bleach at the household level in poor societies as an effective disinfectant (CDC, 2012; WHO, 2007). However, due to the economic disadvantages of importing chemical disinfectants in developing countries, disinfection with herbal and natural materials was proposed by water treatment experts as a financially feasible substitute to the chemical products (Kumar et al., 2017). Reducing the bacterial load in water with natural herbs is an economical and simple method that can be used to obtain safe drinking water in poor areas, mainly if used in point-of-use disinfection at the household level. For example, many types of research have shown the effectiveness of natural plant-based materials such as the Moringa Oleifera seeds. According to (Lea, 2010), adding 200 mg of MO seeds powder in 1 Liter of turbid water could obtain about 80-99.5% turbidity reduction and about 90-99.9% bacterial load reduction. However, the study showed that getting 100% pathogenic bacterial and viral elimination cannot be granted by the natural plant-based herbs as the MO seeds powder. That is why other inexpensive treatment processes are recommended to be used in conjunction to ensure drinking water safety (Lea, 2010).

2.4.4.4. Low-Cost Adsorbents

In general, as stated earlier, the most used conventional methods for the treatment of various aqueous effluents contaminated with heavy metals include chemical oxidation, ion exchange, membrane separation, reverse osmosis, and electro-dialysis, etc. Those chemical treatment technologies are associated with high operating and maintenance costs, making them ineffective in being implemented in the low-income parts of the world. Also, they demand high energy input, making them non-ecofriendly for the environment (Tripathi & Ranjan, 2015). As such, the adsorption techniques have been considered as more effective alternatives for heavy metals treatment purposes. The adsorption methods are generally low in cost and associated with less environmental harm than conventional methods (Renu et al., 2017). The principle of the adsorption process includes the mass transfer of a substance from the liquid phase to the surface of a solid. This is how heavy metals are removed from polluted water by the adsorbent; the heavy metal ions of the contaminated water are transferred to the surface of the adsorbent. The adsorbents used for heavy metal removal exhibit high selective absorption capacity for specific heavy metal ions (Tripathi & Ranjan, 2015). The activated carbon, obtained from carbon-rich materials, is the most common conventional adsorbent for heavy metals removal. Still, it has been perceived with high costs related to the activation processes (Renu et al., 2017). Therefore, many types of low-cost adsorbents have been proposed for heavy metals removal, including natural adsorbents, industrial wastes adsorbents, and agricultural wastes. The most common natural adsorbents include zeolites, clays, and natural polymers such as chitin. The chitin is an attractive low-cost adsorbent because it is the second most abundant polymer after cellulose and can be extracted from various sources such as the crab and shrimp cells, insects exoskeletons, etc. (Tripathi & Ranjan, 2015). The industrial wastes adsorbents are generally produced as low-cost by-products from industrial wastes such as fly ash, coffee husks, tea factory wastes, paper industry, grape stalk wastes, residual slurry from biogas wastes, etc. On the other hand, many studies nowadays focus on adsorbents prepared from agricultural wastes for heavy metals removal, especially for wastewater treatment purposes. This is because adsorbents from agricultural wastes are usually prepared from plant wastes that are widely available, making them very economical and easy to produce. In addition, many adsorbents from agricultural wastes were very selective to various heavy metal ions, making them very effective heavy metals removal methods. However, making adsorbents from organic wastes without treatment or modification can be associated with microbial concerns. It can increase the chemical oxygen demand (COD), biological oxygen demand (BOD), and total organic carbon (TOC) due to the high organic content in them (Tripathi & Ranjan, 2015). Thus, modified and treated agricultural wastes can be proposed as effective and simple methods to enhance water safety in developing countries.

2.5. Sustainable Water Treatment Alternatives

2.5.1. Public Health Concerns on Conventional Water Treatment Methods

Proposing an effective drinking-water treatment system should be based on a comprehensive analysis of the potential advantages and limitations (health, environmental and economic). Thus, it is essential to consider health and environmental hazards associated with the water treatment, even if it was economically feasible (WHO, 2010). Considering the health and ecological aspects of the suggested drinking water treatment approach are inclusive in achieving the SDG 6 goals. Therefore, addressing the public health concerns associated with the common synthetic drinking water coagulants and disinfectants is crucial. Also, nowadays, heavy metals contamination in the water represents a serious problem due to the increase in chemicals and pharmaceutical industry globally (Renu et al., 2017). As presented before, inorganic coagulants, including aluminum-based and iron-based polymers, are the most used coagulants for water and wastewater treatment. Moreover, chlorination is the most widely used disinfection method of water supplies. On the other hand, the common conventional methods for hazardous pollutants treatment, such as heavy metals, require advanced technologies such as ion exchange, membrane filtration, or using conventional adsorbents such as activated carbon (Renu et al., 2017). Many studies have reported evidence of the ineffectiveness of these water treatment methods' long-term application in developing countries. Also, the conventional water treatment products have been perceived with harmful health effects for the long-term exposure. They are not eco-friendly, and the advanced treatment technologies are not economical for long-term applications in developing countries.

The use of metal coagulants in water treatment processes has raised public health concerns about their toxic impacts on human health and the environment (Okaiyeto et al., 2016). The significant health effects of metal coagulants come when metal ions such as Al or Fe hydrolyze in water to form a series of metal hydrolysis species. In many cases, aluminum coagulants can result in untended high levels of this trace metal in water. The exposure of humans to aluminum ions has been linked to neurotoxicity, increasing the risk of Alzheimer’s disease (Krupińska, 2020). The coagulants and organic chemical coagulants, especially the non-biodegradable coagulant products, are associated with chronic toxic effects to the environment related to soil and water pollution. Additionally, organic chemical flocculants and coagulants are costly to dispose of and can be a source of pollution (Okaiyeto et al., 2016).

On the other hand, although highly effective, chemical disinfectants such as chlorine disinfection are linked with potential health risks associated with chlorination byproducts. Several research studies have documented the possible carcinogenic and other health outcomes of disinfection byproducts (DBPs). When added to water, the chemical disinfectants might react with the natural materials present in water, forming the disinfection byproducts such as the Trihalomethanes (THM) and Haloacetic acids (HAAs), chlorite, and bromate. Possible health risks of those DBPs include early-term miscarriage, bladder cancer, and can also be linked to congenital disorder and frequent loss of pregnancy (EPA, 2013). In response to those public health concerns, safer disinfection alternatives which are acerbated by not removing the organic content before application, have been proposed. Using non-chemical disinfectants such as UV irradiation can represent an elementary strategy to reduce the concentration of DBPs. This physical method is very effective in inactivating most viruses, spores and is not associated with harmful health effects. However, UV disinfection is not as cost-effective as chlorination, making it not economical to be applied in developing countries (EPA, 2013).

As such, cost-effective and natural water treatment alternatives could represent valuable solutions to avoid using chemical agents. Sand filtration, ceramic water filtration, and infiltration techniques are considered natural water treatment methods that can reduce the microbial load in the water. As presented earlier, eco-friendly materials such as the Moringa Oleifera seeds can achieve effective water treatment results such as significant turbidity, microbial load reduction, and removal of specific heavy metals ions. Still, there are limitations in guaranteeing the destruction of pathogenic microorganisms present in water by using those proposed environmentally friendly alternatives. Thus, ongoing research should learn more about cost-effective, eco-friendly water treatment approaches (Okaiyeto et al., 2016).

2.5.2. Environmentally Friendly Simple Water Treatment Alternatives

The world is rich with natural materials that can be used sustainably in various fields of applications. Natural raw materials such as agricultural and food wastes are being generated and lost, which entails poor use of resources and negative environmental impacts. Many researchers used agricultural solid wastes as low-cost adsorbents and coagulants for water treatment purposes. The adsorption in ecological technology for water treatment is a process by which specific contaminants and pollutants are effectively removed using eco-adsorbents. Several earlier studies elaborated the investigations about the relation of the structure and components of eco-adsorbents to the adsorption of specific contaminants in water (Bhatnagar, 2012). Accordingly, agricultural waste materials such as eggshells and banana peels were proposed as economically inexpensive alternative adsorbents for water and wastewater treatment applications in developing countries. The outcomes of earlier studies and researches showed that eco-adsorbents such as Moringa Oleifera, banana peels, eggshells, tomato peels, citrus peels, and others have other advantages besides being costly-effective. They can provide the water with essential minerals, making them safer alternatives than the chemical water treatment products, especially if technical mistakes happen during the treatment process (Bhatnagar, 2012).

2.5.2.1. Water Treatment by Banana Peels

Studies have shown that banana peels could be a potential low-cost eco-adsorbent/coagulant for water and wastewater treatment in developing countries. Banana peels can effectively remove turbidity from water and can also be used to purify water from various toxic heavy (John et al., 2017; Leong, 2018). According to John et al., 2017, banana peels could achieve up to 95% or more turbidity removal under experimental conditions that enhance adsorption factors such as the contact time, dosage concentration, and the physio-chemical characteristics of the water or wastewater to be treated. John et al. concluded that the optimum dosage of banana peels powder to obtain the desired turbidity is relative to the turbidity concentration in water. The banana peels powder coagulant achieved the best turbidity removal at the maximum dose ranges. The dose range was investigated from 0.2 g/L to 1 g/L, and turbidity removal was observed to be 96.7% at a dosage of 1 gram of banana peel powder at 160 NTU (John et al., 2017). After reaching the optimum dose of banana peels, the turbidity reduction starts to decline. Thus, the banana peels exhibit similar characteristics to conventional coagulants when used as a coagulant for turbidity removal (Mokhtar and Kristanti, 2019). Therefore, the optimum dosage of the banana peels for turbidity removal depends on the physio-chemical characteristics of the water sample. Still, it is hard to interpret a direct relation between the coagulant dose and turbidity removal for banana peels. That's why Mokhtar and Kristanti recommended optimizing the banana peels powder dosage by using the jar test experimental procedure and expanding the range of coagulant doses (Mokhtar and Kristanti, 2019).

Additionally, researchers found that banana peels could be an effective, low-cost method for removing heavy metals from wastewater or water under emergency conditions. The banana peels constitute components with high metal-binding characteristics such as lignin, cellulose, hemicellulose, and pectin extractions. Several studies showed that banana peels could absorb heavy metal ions such as Cd^{2+}, Co^{2+}, Cu^{2+}, Ni^{2+}, Pb^{2+}, Cr^{2+} and Zn^{2+} from contaminated waters (Arunakumara, 2013; Leong, 2018). Those studies found that the adsorption capacity depends on several factors: the pH solution, adsorbent dose, contact time, heavy metals concentration, and the physio-chemical characteristics of the water or wastewater sample. As such, Darges et al. study showed that removing heavy metals such as zinc and iron from wastewater is strongly dependent on the banana peels' adsorbent dose contact time. The highest removal rates of zinc and iron were 81% and 74%. Those were achieved at the highest dose (3g/L) and after 6 hours of contact time (Darge et al., 2015).

However, the adsorption conditions can vary depending on the water or wastewater sample's physical-chemical characteristics (Leong, 2018). Hossain et al. reported that the appropriate dosage to remove copper ions by banana peels is strongly dependent on the contact time and initial concentration of copper in the water sample. The highest removal rate was 88% for the water sample with lower copper concentration (10 ppm) which was obtained at an optimum dose of 5g/L and after 30 min contact time (Hossain et al., 2012) (Arunakumara, 2013). Another study conducted by Anwar et al. studied the effect of banana peels adsorbent dosage in the range 10-90 g/L. The study showed that the removal rates decline at high doses, which can be related to the availability of the active binding sites. The optimum doses were 30 g/L, achieving 89.2% Cd^{2+} removal, and 40 g/L achieving 85.3% Pb^{2+} removal (Anwar et al., 2012) (Arunakumara, 2013). The contact time can vary depending on the heavy metals solution component, and most studies confirmed that the adsorption of metal ions would decline progressively with time after reaching equilibrium (Arunakumara et al., 2013).

Moreover, another study conducted by Arifiyana & Devianti, showed that the pH was one of the factors that highly affects the absorption of heavy metal ions, especially solutions that are contaminated with various heavy metal ions. The pH factor affects the banana peels' adsorbent surface selectivity to the heavy metal ions, which can change the heavy metal ions' competition in the absorption process. For example, in Arifiyana & Devianti study, which was conducted on Co (II) and Ni (II) synthetic solution, the optimum absorption of Ni and Co was at pH 4. The absorption of nickel and cobalt ions decreased at pH 5; then, it slightly increased again at pH 6 and 7 due to the reduction of the H^+ ions in the solution. On the other hand, the study reported that the absorption of heavy metal ions in an alkaline solution would not be effective. In an alkaline solution, hydroxy species of the heavy metal ions would form as sediments in the solution (Arifiyana & Deviant, 2021). Thus, different conditions should be used over banana peels to optimize their application as a low-cost adsorbent for heavy metals removal.

2.5.2.2. Water Treatment by Eggshells

Studies have shown that eggshells can be effective eco-adsorbents. Eggshells have unique characteristics because of their calcium carbonate content ($CaCO_3$ represents more than 94% of the eggshells content), which exhibits a high binding affinity to many contaminants present in water (Makuchowska-Fryc, 2019). The eggshells membrane showed a high binding affinity to various heavy metals such as Cr, Cu, Ni, Cd, Pb, Mn, Fe, Co, Zn, Mg, and Ca (Orłowski et al., 2017). In addition, the eggshells can be converted into an effective antimicrobial agent when converting the CaCO3 into CaO (calcium oxide) by combustion (Ohshima et al., 2015). Under the appropriate water treatment conditions (pH, initial concentration, dosage, and contact time), the eggshells adsorbents can obtain effective treatment results and replace conventional products such as bentonite clays (Makuchowska-Fryc, 2019). In addition, obtaining the activated carbon from eggshells can have the potential to replace expensive traditional products like Powdered Activated Carbon (PAC), Granular Activated Carbon (GAC), and Extruded Activated Carbon (EAC). Those are among the most effective adsorbents for water and wastewater treatment applications (Carvalho et al., 2011). Those are highly porous materials that give a large surface area to absorb various contaminants and toxins. Similarly, carbonized eggshells would be a cost-effective alternative to the conventional adsorbents and obtain similar water treatment results (Carvalho et al., 2011). In water treatment applications, similar to the banana peels adsorbents, the eggshells' adsorption efficiency depends on several factors such as the solution pH, adsorbent dose, contact time, initial concentration of the contaminants, and the physio-chemical properties of the water sample to be treated (Tizo et al., 2018).

Tizo et al. investigated the cadmium adsorption by the eggshells adsorbents cadmium from synthetic cadmium solution. The optimum removal rate of cadmium was recorded as 73% at 150 ppm initial concentration, 75 min contact time, and 0.75 g adsorbent dose (Tizo et al., 2018). Another study conducted by Bhaumik et al. (2012) proposed a kinetic model showing that the eggshell powder has performed well in removing fluoride from an aqueous solution under certain conditions. This study showed that the pH solution greatly influenced eggshells' adsorption capabilities, and the optimum condition was at pH 6. The optimum fluoride removal rate was at 5 ppm initial fluoride concentration. Thus, increasing the first fluoride concentration reduced the percentage of fluoride removal until equilibrium reached a higher fluoride concentration. Increasing the contact time to 120 min influenced the fluoride removal rate; then, there was no further increase in fluoride adsorption.

Another study conducted by Annane et al. (2021) showed similar pH conclusions related to the cadmium ions absorption by the eggshells adsorbents. Annane et al. study showed that the maximum removal of cadmium of 99% was achieved between pH 5-7. Beyond pH 7, the cadmium removal efficiency decreased due to the precipitation of cadmium (II) hydroxide (Annane et al., 2021). On the other hand, Annane et al. study showed different optimum conditions than Tizo et al. study regarding the selected dose, contact time, and initial cadmium ions concentration, which more effective cadmium removal results. The study showed that the highest cadmium removal of 99% was achieved in 10 min contact time, adsorbent dose of 0.8 g/L, pH of 5, and the initial cadmium concentration is less than 100 ppm (Annane et al., 2021). Hence, it can be inferred that the optimum conditions for removing specific water contaminants by the eggshells adsorbent vary based on the pollutants to be removed and the water sample physical-chemical characteristics. The modeling and optimization techniques can also vary according to the study scope, study settings, and research objectives (Bhaumik et al., 2012).

2.5.2.3. Potential of Protein Coagulants in Water Treatment

Many studies have evaluated the effectiveness of proteins obtained from natural materials as low-cost and eco-friendly alternatives to conventional coagulants in drinking water treatment. Sulaiman et al. showed that the protein content in Moringa

Oleifera produces positive charges in water solutions, attracting all the negatively charged particles that cause turbidity in water, such as clay, silt, bacteria, and other harmful substances (Sulaiman et al., 2017). The Moringa Oleifera seeds coagulant could achieve up to 99% turbidity removal, including the inactivation of some harmful microorganisms present in water (Sulaiman et al., 2017). Another study conducted by Shan et al. showed that the protein content in the MO seeds exhibited a high affinity to specific heavy metal ions such as iron, copper, and cadmium. The study showed that MO seeds achieved the following removal rates from a river water sample: 75% lead ions reduction, 98% cadmium ions reduction, and 100% reduction of iron ions (Shan et al., 2017). In addition, other natural materials such as mustard seeds are rich in protein content and have been applied by several researchers for water treatment purposes. Bodlund study evaluated the effectiveness of the protein content in mustard seeds, and their water treatment efficiency was comparable to the Moringa Oleifera seeds. The Mustard seeds showed effective turbidity removal, specific heavy metals removal, and antimicrobial properties (Bodlund, 2013). However, mustard seeds could achieve similar results to the Moringa Oleifera seeds but at higher doses. Hence, using Moringa Oleifera seeds has the cost advantage of Mustard seeds since they work more effectively at lower doses (Bodlund, 2013). Thus, ongoing studies can investigate further different types of natural proteins to remove particular contaminants from polluted water sources since they are sustainable to the environment and can enhance drinking water safety (Hendrawati et al., 2015).

As presented before, it is crucial also to determine the optimum factors and conditions that optimize the treatment cost of those natural protein materials and achieve desirable water treatment results. Hendrawati et al. showed that obtaining desirable turbidity removal rates is related to the conditions used to treat the polluted water (coagulant dose, initial concentration, contact time, physio-chemical parameters, pH, and other) and the physio-chemical characteristics of the protein coagulant. For example, a desirable size for the Moringa Oleifera seeds powder to remove turbidity would be 300 nm; a smaller or bigger size would disturb the coagulation efficiency of the MO seeds powder. The best Moringa Oleifera seeds coagulant dose could be 50-200 mg/L if the first turbidity were higher than 150 NTU, or 10-50 mg/L if the first turbidity was lower than 50 NTU (Hendrawati et al., 2015). Yet, understanding the coagulation properties of the natural protein coagulants is still a constraint. Although many studies showed that the significant coagulant correspondence between the Moringa Oleifera seeds and Mustard seeds is the protein component, further studies are still needed to understand the compounds' chemical-physical characteristics and the coagulation activity conditions (Hendrawati et al., 2015). In addition, the cost-effectiveness of eco-friendly protein coagulants and adsorbents needs further investigation to conclude their applicability in developing countries and rural regions (Hendrawati et al., 2015).

CHAPTER 3

METHODOLOGY

3.1. Overview of the Chapter

This chapter presents the study design framework, and the experimental procedures followed to evaluate the application and effectiveness of eco-friendly adsorbents and coagulants in water treatment. The purpose is to remove various contaminants from water and ensure its safety as per WHO Guidelines for Drinking Water. The methodology illustrates the study design and variables, sampling techniques, analytical tools, methods used to conduct the experiments, and statistical tools used to analyze and report results.

3.2. Materials and Methods

This pilot study focuses on investigating the performance of eco-adsorbents and novel natural materials in the removal of specific types of water pollutants. In particular, banana peels and eggshells eco-adsorbents/coagulants segregated from organic garbage wastes were studied. Additionally, this pilot study investigated the potential use of animal-based proteins such as ovalbumin protein as a novel eco-adsorbent/coagulant for water treatment.

3.2.1. Instrumentation, Materials, Reagents and Software

This pilot study was conducted based on experimental quantitative research, and the laboratory study was held at the University of Qatar. The following instrumentation, reagents, and software were used to analyze the tested eco-adsorbents/coagulants' performance in turbidity removal, pathogenic microorganisms' destruction, and heavy metals removal.

3.2.1.1. Turbidity Removal

- *Instrumentation and Materials*

  Volumetric Flasks and Beakers: 1000 ml, 250 ml, and 100 ml, Spatula, Filtration Equipment, KERN770 Analytical Balance, Senslon 7HACH,Conductivity Meter, HACH DR 5000 UV Spectrophotometer, 2100P Portable Turbid Meter, Senslon 7HACH , PH Meter, Digital Titrator.

- *Reagents*

  Distilled Water, Sulfuric Acid Standard Solution (0.02N), Ethanol, Phenolphthalein Indicator.

- *Software*

  Minitab 19 Software.

3.2.1.2. Destruction of Pathogenic Microorganisms

- *Instrumentation and Materials*

  Plastic Test Tubes: 25 ml, and 45 ml, Membrane Filtration Unit with Pump , Millipore Vacuum Pump XF54 230 V, Incubator, Shaker Incubator, KERN770 Analytical Balance, Spatula, Inoculation loop, Nylon Membrane Filters-0.45 Microns, Nutrient Agar plates, DensiCHEK Plus Instrument, Laboratory Vortex, Escherichia coli (E. coli stains ATCC® 25922).

- *Reagents*

  Luria-Bertani (LB) broths, Phosphate Buffer Saline Solution, Ethanol, and Distilled Water.

3.2.1.3. Heavy Metals Removal

- *Instrumentation and Materials*

  Volumetric Flasks and Beakers: 1000 ml, 250 ml, and 100 ml, 100 ml Measuring Cylinder, 15 ml Testing Tubes, Lab Used Grinder (High-Speed Multi-function comminutor), Spatula, Filtration Equipment, KERN770 Analytical Balance, Orbital Laboratory Shaker, Hot Air Oven, 48000 Furnace, Inductively Coupled Plasma Mass Spectroscopy (ICP-MS).

  The Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) has been selected for the analysis of the heavy metals in this study over the atomic absorption spectroscopy (AAS). Although ICP-MS is more expensive, this study's required elemental analysis contributed to the selection of the ICP-MS due to its desirable features over the AAS. The ICP-MS is more sensitive, capable of detecting multible elements (more than 20) simultaneously, has outstanding detection limits (can detect limits up to 0.01 mg/L for many elements), has high sample output, and can distinguish between isotopes. On the other hand, the AAS does not have those features compared to the ICP-MS and cannot detect various heavy metal elements in the solution simultaneously, unlike the ICP-MS (Wilschefski & Baxter et al., 2019).

- *Reagents*

  Iron (Fe), chromium (Cr), cadmium (Cd), zinc (Zn), and lead (Pb) stock solutions: 1000 ppm, 200 ppm and 50 ppm, cadmium (Cd) and lead (Pb) stock solutions: 300

ppm, 150 ppm, 80 ppm and 10 ppm, Hydrochloric Acid HCl, 10-15%, Nitric acid (HNO3), Deionized Water and Distilled Water.

- *Software*

  Minitab 19 Software.

3.2.2. Adsorbent Samples Preparation

3.2.2.1. Banana Peels

Banana peels were segregated from garbage organic wastes, cleaned, dried, and labeled to be used in the raw and carbonized forms**:**

- *Preparation of Raw Banana Peels (RBP) Adsorbent*

Domestic banana peels wastes were collected from local hypermarkets in Doha, Qatar. The peels were washed several times with tap water and distilled water, dried in a hot air oven at 80 °C for three consecutive days. The dehydrated banana peels were grinded through a laboratory grinder to obtain a 300 µm particle size powder. Finally, the grinded peels were labeled as “banana peels raw.” Enough amounts of the RBP powder were kept aside for the carbonized banana peels preparation. The laboratory procedural steps used to prepare the RBP adsorbent are summarized in figure 3.1.

Figure 3.1: Raw Banana Peels (RBP) Adsorbents Preparation

Additionally, for the destruction of pathogenic contaminants, the RBP extract sample was further soaked in distilled water (200 mg/10ml), homogenized at 2500rpm, and placed in a shaker incubator for 30min.

- *Preparation of Carbonized Banana Peels (CBP) Adsorbent*

The set-aside, unlabeled dehydrated RBP powder was used for the CBP preparation. The dehydrated RBP was burnt in a laboratory furnace at 500 °C for 2 h to be converted into activated carbon. Finally, the CBP was labeled as “Banana 500 °C.” The laboratory procedural steps used to prepare the CBP adsorbent are presented in figure 3.2.

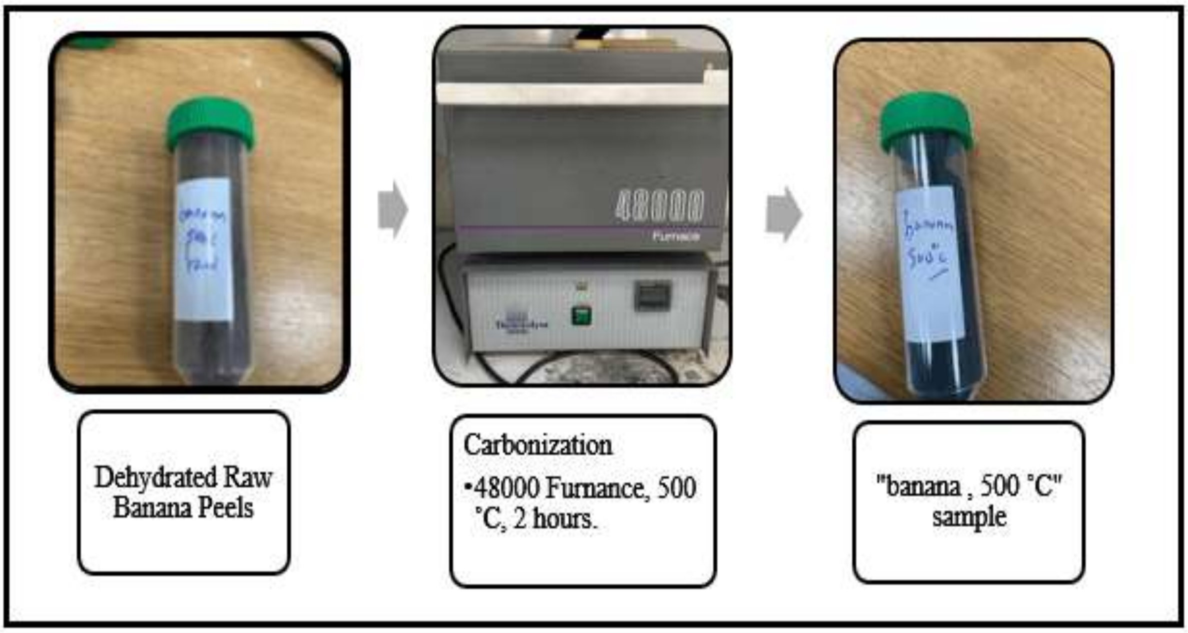


Figure 3.2: Carbonized Banana Peels (CBP) Adsorbents Preparation

Additionally, for use in the destruction of pathogenic contaminants, the CBP extract sample was further soaked in distilled water (20 mg/10ml, 50 mg/10ml, 100 mg/10ml, and 200 mg/10ml), homogenized at 2500rpm, and placed in a shaker incubator for 30min.

3.2.2.2. Eggshells (ES)

Similar to the banana peels, eggshells (ES) were also segregated from garbage organic wastes, cleaned, dried, divided separately and labeled.

- *Preparation of Raw Eggshells (RES) Adsorbent*

Domestic eggshells wastes were collected from the market. The eggshells wastes were washed several times with tap water and distilled water. After washing, the eggshells were boiled for 15 min to destroy pathogenic microorganisms. Then, they were dried in a hot air oven at 80 °C for three days. The dehydrated eggshells were grinded to obtain a powder of 300 µm particle size. Finally, the dehydrated shells were labeled as “Eggshells Raw.” Enough amounts of the RES powder were kept aside for the carbonized eggshells preparation.

The laboratory procedural steps for used to prepare the RES adsorbent are presented in figure 3.3.

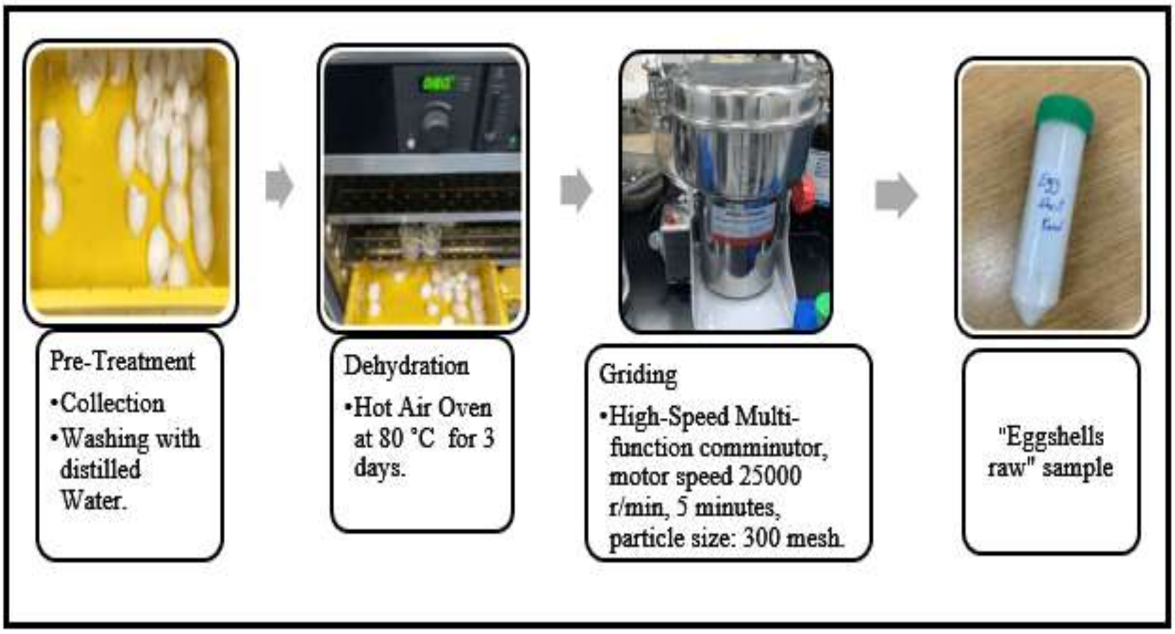


Figure 3.3: Raw Eggshells (RES) Adsorbent Preparation

Additionally, for the destruction of pathogenic contaminants, the RES extract sample was further soaked in distilled water (200 mg/10ml), homogenized at 2500rpm, and placed in a shaker incubator for 30min.

➢ *Preparation of Carbonized Eggshells (CES) Adsorbent*

The set-aside, unlabeled dehydrated RES powder was used for the CBP preparation. The dehydrated RES was burnt in a laboratory furnace at 500 °C for 2 h to be converted to activated carbon. Finally, the CES was labeled as “Eggshells 500 °C.”

The laboratory procedural steps for used to prepare the CES adsorbent are presented in figure 3.4.

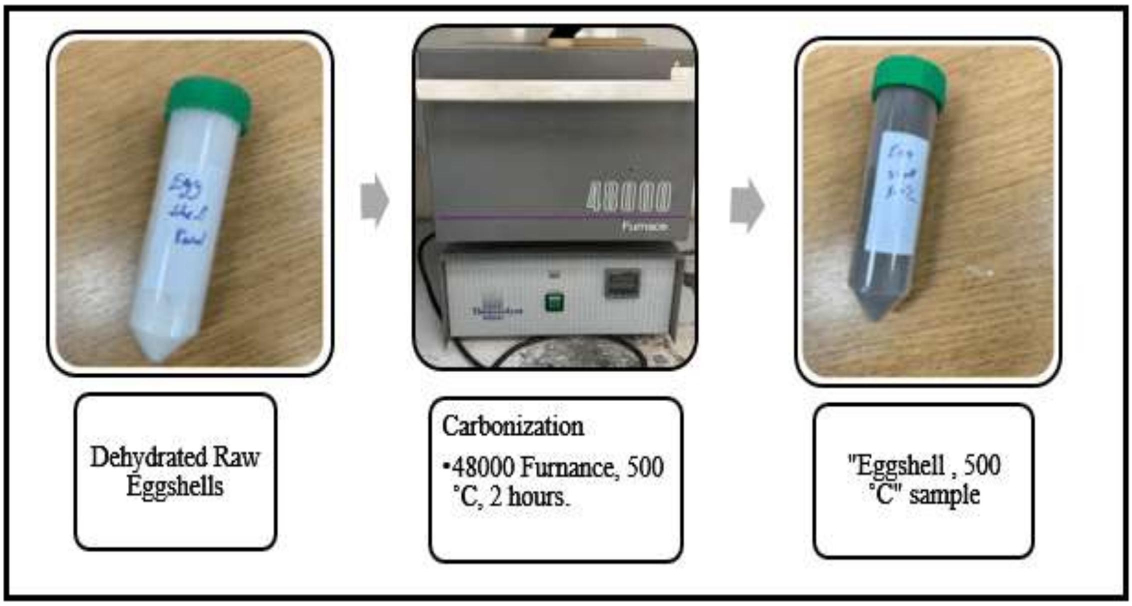


Figure 3.4: Carbonized Eggshells (CES) Adsorbent Preparation

Additionally, for use in the removal of pathogenic contaminants, a CES extract sample was further soaked in distilled water (20 mg/10ml, 50 mg/10ml, 100 mg/10ml, and 200 mg/10ml), homogenized at 2500rpm, and placed in a shaker incubator for 30min.

3.2.2.3. Ovalbumin Protein

Certified ovalbumin protein extract from the egg whites was purchased from MEDTECH CORPORATION, USA (batch number: SLBS4311). The ovalbumin protein was used to test the efficiency of animal-based proteins in treating water. The purchased product was a technical crystal powder from egg whites, so it did not require further preparation before use. Additionally, for the use in the removal of pathogenic contaminants, the ovalbumin protein extract sample was further soaked in distilled water (200 mg/10ml), homogenized at 2500rpm, and placed in a shaker incubator for 30min.

3.2.2.4. Poly-aluminum Chloride

Technical coagulant powder grade of poly-aluminum chloride (PAC) was purchased locally from Qatar (Water Treatment Drinking Grade PAC 30% Poly Aluminum Chloride) and used as a control to test the effectiveness of the eco-friendly materials. This is because PAC is one of the most common traditional coagulants. The purchased PAC product was ready for use without additional preparation. Additionally, for use in the reduction of pathogenic contaminants, the PAC extract sample was further soaked in distilled water (200 mg/10ml), homogenized at 2500rpm, and placed in a shaker incubator for 30min.

3.2.3. Preparation and Analysis of Water Samples

3.2.3.1. Water Samples and Stock Solution

3.2.3.1.1. Water Samples

Water samples were collected from a well in an agricultural area located in Al-Khor City, Qatar. Table 3.1 presents the overall quality parameters of the collected sample.

Table 3.1: Well Water Quality in Comparison to Qatar Standards (Al-Naama, 2014) and WHO Guidelines for Drinking Water (WHO, 2017).

Quality Parameters	Sample Values	Qatar Standards	WHO Guidelines for Drinking Water
Physical Parameters			
Color (TCU)	7.3	15	15
Turbidity (NTU)	235	4	5
Total Dissolved Solids, TDS (mg/L)	436	110-250	500
Chemical Parameters			
pH	7	7-8.3	6.5-8.5
Alkalinity (mg/L)	31.2	60-120	-

TCU: True Color Units, NTU: Nephelometric Turbidity Units

Additionally, to investigate the effectiveness of the eco-adsorbents/ coagulants' turbidity removal, stock solutions low moderate and high turbidity were prepared as presented in table 3.2.

Table 3.2: Characteristics of Turbid Water Samples

Quality Parameters	Low Turbid Water (Sample 1)	Medium Turbid Water (Sample 2)	High Turbid Water (Sample 3)
Physical Parameters			
Turbidity (NTU)	27	52	103
Total Dissolved Solids, TDS (mg/L)	174	199	310
Color (TCU)	4.3	5.2	5.7
Chemical Parameters			
pH	7.2	7.2	7.3
Alkalinity (mg/L)	48	49	49

TCU: True Color Units, NTU: Nephelometric Turbidity Units

3.2.3.1.2. Stock Solutions

- *E. coli Stock Solution*

The Escherichia coli (E. coli stains ATCC® 25922) pathogenic bacteria were firstly grown in Luria Broth (LB) overnight at 37 °C to mid-log phase. Then, a pure bacteria culture was prepared by isolating the E. coli on a nutrient agar plate. The E. coli stock was prepared by adding four bacteria colonies from the agar plate into 6 ml of phosphate-buffered saline (PBS) to obtain a concentration of 0.5 McFarland (1X10^8 CFU/mL).

- *Fe, Cr, Cd, Zn, and Pb Stock Solutions*

Two main concentrations containing multiple heavy metals elements were prepared for the initial screen of the effectiveness of eco-adsorbents in heavy metals removal at lower and higher concentrations. Firstly, a 1000 ppm stock solution of iron (Fe), chromium (Cr), cadmium (Cd), zinc (Zn), and lead (Pb) was prepared by adding 1 g of each of the following chemical substances (Lead (II) Nitrate, Zinc Nitrate Anhydrous, Potassium Chromate, Chromium (III) nitrate nonahydrate, Cadmiumnitrate-4-hydrate, and Iron (III) Nitrate nonahydrate) in 1 liter of deionized water . The 1000 ppm stock solution was used to prepare working solutions ranging from 50 to 200 ppm and 50 ppm.

- *Chromium and Lead Stock Solution*

Three (low, middle, and high) concentrations ranges of lead and chromium were prepared. Firstly, the 300 ppm main stock solution of chromium and lead was prepared in a volumetric flask by dissolving 2.3 g of Chromium(III) nitrate nonahydrate ($CrH_{18}N_3O_{18}$) and 0.48 g of Lead(II) nitrate ($Pb(NO_3)_2$) in 1 liter deionized water.

The 300 ppm stock solution was used to prepare the three concentration ranges of 10, 80, and 150 ppm.

3.2.3.2. Analytical Methods

The physical, chemical and microbiological water quality parameters were analyzed in accordance with standard methods recommended by American Water Works Association (AWWA), American Public Health Association (APHA), and Water Environment Federation (WEF) (APHA, AWWA & WEF, 2017). Table 3.3 summarizes the water quality parameters, the analytical methods, and the instruments used for the analysis.

Table 3.3: Water Quality Parameters Tested and Analytical Methods Used (APHA, AWWA, WEF, 2017)

Analytical parameter		**Standard analytical method**	**Type of analytical equipment**
physical	TDS	ADD	Senslon 7HACH,Conductivity Meter
	Color	Spectrophotometry	HACH DR 5000 UV Spectrophotometer
	Turbidity	Electronic-Turbidity Method	2100P Portable Turbid meter
Chemical	pH	Electrometric Measurement	Senslon 7HACH , PH Meter
	Alkalinity	Titration Method using Sulfuric Acid Standard Solution(0.02N)	Digital Titrator
	Trace Metals	Spectrophotometry	Inductively Coupled Plasma Mass Spectroscopy (ICP-MS)
Microbiological	Escherichia coli.	Membrane Filter Technique	Millipore Filtration

The stock solutions for trace metal analysis were prepared in the General Chemistry Lab at Qatar University and analyzed in the Environmental Science Center at Qatar University. Additionally, the water samples' physical and chemical parameters as per table 3.3 were analyzed in the Main Lab of the Environmental Research Unit at the Arab Center for Engineering Studies, Qatar. On the other hand, the preparation of stock solutions for the microbiological analysis and the testing was done by the Biomedical Research Center at Qatar University.

3.3. Experimental Designs

3.3.1. Turbidity Removal

The Jar Test apparatus was used to determine the coagulation efficiency of the eco-adsorbents/coagulants and compare them to traditional coagulants such as poly-aluminum chloride. The coagulants were tested under the same experimental conditions. The main objective of the Jar test was to identify the optimal dose of coagulant that will reduce the turbidity optimally without changing the overall water quality as indicated by TDS, Color, pH, and Alkalinity. The selected input variables were the coagulant dosage and initial turbidity, as presented in table 3.6. Other input factors such as the pH, contact time, and mixing speed were fixed, as shown in table 3.4. The traditional jar test experiments were carried out at those ranges to optimize the coagulation conditions.

Table 3.4: Jar Test Experiments

Jar Test 1						
Variables	JAR 1	JAR 2	JAR 3	JAR 4	JAR 5	JAR 6
AD (mg)	20	40	80	160	320	640
Ti (NTU)	27					
(rpm) and CT	Slow Mix: 30 rpm for 20 min					

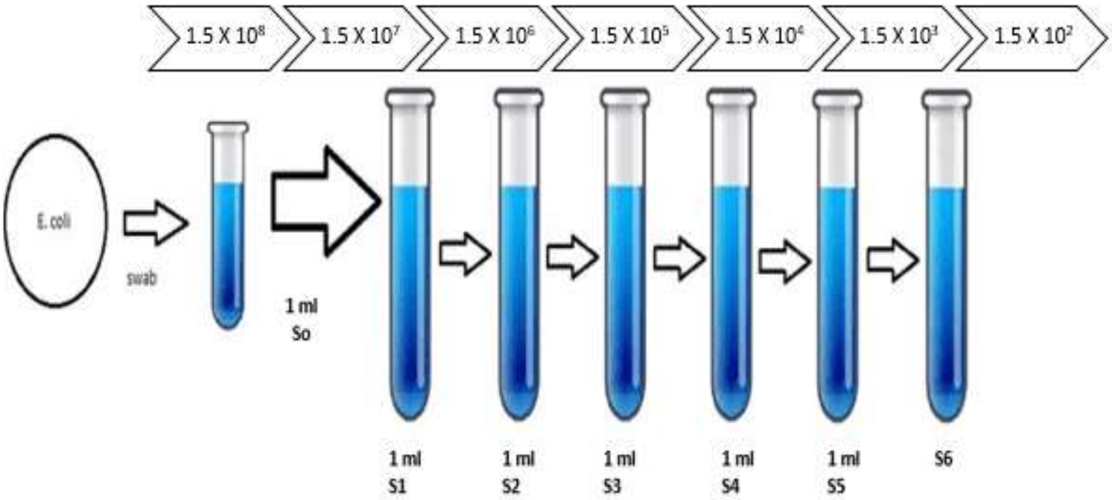


Figure 3.5: Serial Dilution Procedure. E. coli CFU/ml.

AD: Adsorbent Dose (mg), Ti: Initial Turbidity (NTU), CT: Contact Time (min), pH_i: Initial Ph, TCU: True Color Units, NTU: Nephelometric Turbidity Units

3.3.2. Destruction of Pathogenic Microorganisms

The microbiological analysis was conducted by using the serial dilution method as shown below by figure 3.5.

The main objective was to identify the optimal dose for the tested eco-adsorbents/coagulants compared to the PAC that optimally destroys the E. coli bacteria.

The selected input variable was the extract concentration dose (mg/10ml). The fixed input factors were the contact time (30 min) and incubation temperature (37 °C). Initial screening was performed on carbonized banana peels to identify the dose to destroy E. coli bacteria optimally. The E. coli destruction by carbonized banana peels was tested at the following dose concentration ranges: 20, 50, 100, and 200 mg/10ml. The optimal dose concentration was selected for experimental testing for the rest of the eco-adsorbents/coagulants.

3.3.3. Chromium and Lead Removal

3.3.3.1. Selection of Design Factors Range

- Initial Screening for the Heavy Metals Analysis

The adsorption of Fe, Cr, Cd, Zn, and Pb by the RBP, CBP, RES, and CBP adsorbents was tested by adding 50 mg from the adsorbents' powder to 15 ml water sample tubes. Then, 13 ml from the heavy metal containing solutions (50 ppm and the 200 ppm stock solutions) were transferred to the sample tubes. This resulted in a total of eight samples. All the samples were then shaken for 20 min at a laboratory shaker. The samples were then filtered, and 1% of concentrated nitric acid was added to each sample in order to prevent the metals from depositing on the inner side of the ICP tube. The heavy metals concentrations, before and after treatment by the three different adsorptions, were analyzed through the ICP-MS. The raw banana peels, carbonized banana peels, raw eggshells, and carbonized eggshells worked most effectively in lead and chromium adsorption. Thus, the experimental design for trace metals was carried, only, on chromium and lead contaminant removal.

The design factors were selected to obtain a broader range of analysis according to the initial screening results as presented in table 3.5.

Table 3.5: Heavy Metals Experimental variables (Low, Mid and High)

Factors	Low Level	Midpoint	High Level
Contact Time (min)	20	70	120
Chromium and Lead Concentration (ppm)	10	80	150
Adsorbent Dose (mg/13 ml)	20	60	100

3.3.3.2. Design of Experiment (DOE)

Placket-Burman Design (PBD) was created by Minitab 19 software to develop the experimental design for the banana peels adsorbents (raw and carbonized). On the other hand, the experimental conditions for the eggshell adsorbents (raw and carbonized) were selected by the Box Behnken surface (BB) design. The chosen design factors were the adsorbent dose, initial heavy metals concentration (Chromium and lead), and contact time. The design factors values fall at combinations of the high and low factor levels and their midpoints, as shown in table 3.5. A random set of 16 experiments were generated by each design for the banana peels and eggshells adsorbents. The Placket-Burman and Box-Behnken designs identified the effects of adsorbent dose, adsorbate concentration, and contact time on the response variable, which is the removal (%R) and adsorption capacity. The design worksheets created by

Minitab 19 for both eggshells and banana peels adsorbents are presented in Appendix 2 (Tables A2.1 and A2.2).

3.4. Data Analysis

3.4.1. Turbidity Removal

The WHO Guidelines for Drinking Water were used as a reference to determine water safety. Additionally, line charts were used to determine the correlation between the coagulant dosage and the response variables (turbidity, TDS, color, pH, and alkalinity) at the three respective turbidity ranges: low (27 NTU), medium (50 NTU), and high (103 NTU). The ANOVA statistical method by Minitab 19 software was used to analyze the correlation between the turbidity removal mean and the adsorbent dosage at a 90% confidence level. The ANOVA interval plots were used to test for any linear correlation to show the turbidity removal mean data (27, 52, and 103 NTU) with different coagulant dosages.

3.4.2. Destruction of Pathogenic Microorganisms

The experimental design was set to study the effect of the tested doses of the eco-adsorbents/coagulants on the destruction of E. coli. The dose-effect impact was compared to that of the traditional coagulant PAC (Positive control). The presence of E. coli colonies after treatment with the tested eco-adsorbents/coagulants was determined using a digital colony counter and computing the E. coli removal rate, which shows the percentage of E. coli reduction to the negative control sample.

E. coli Reduction Rate %= $(\mathrm{nC} - \mathrm{nM})/\,\mathrm{nC} \times 100\%$

3.4.3. Chromium and Lead Removal

As presented in the section on experimental design, statistical analysis of chromium and lead removal rates by banana peels and eggshells adsorbents were computed by Minitab 19 software using the ANOVA (Analysis of Variance), normal probability plots, Pareto Charts, and the Response Optimizer. The factorial regression analysis was used for raw and carbonized banana peels adsorbents to compute statistical analysis at a 95% confidence level. On the other hand, the response surface regression analysis was used for raw and carbonized eggshells adsorbents to compute statistical analysis at a 95% confidence level. Additionally, the chromium and lead removal rates (R %), and adsorption capacity, were calculated by using the following equations:

$$(\%\mathrm{R}) = \frac{\mathrm{C_0 - C_e}}{\mathrm{C_0}} \times 100\%,$$

R%: Removal Rate of the measured impurity, C_0 *(mg* L^{-1}*): Initial concentration of impurity in solution (adsorbate),* C_e *(mg* L^{-1}*): adsorbate concentration at equilibrium.*

$$(\mathrm{q_e, mg/g}) = \frac{\mathrm{C_0 - C_e}}{\mathrm{W}}\,\mathrm{V},$$

(q_e) *: Adsorption capacity,* (q_e) *V: Volume of the solution in liter, W: Weight of the coagulant (g).*

3.5. Limitations of the Study

This preliminary pilot-scale study demonstrates the potential and feasibility of eco-friendly materials in enhancing water safety and reducing the use of chemicals in water treatment to remove the specified types of contaminants. The significant limitations encountered were mainly related to working outside AUB Campus and the coordination needed among labs at Qatar University under the COVID-19 lockdown, regulations, and limited physical access primarily associated with resources and settings restrictions. For this reason, it was challenging to experiment on the effectiveness of ovalbumin protein on heavy metal removal as it would require different experimental designs, complementary to those used for the eco-adsorbents/coagulants tested.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Overview of the Chapter

This chapter presents and discusses the efficiency of removal of specific water contaminants by eco-adsorbents/coagulants (eggshells, banana peels, and ovalbumin protein) compared to traditional poly-aluminum chloride (PAC) coagulants. The dose identified for each eco-adsorbent/coagulant product was based on the optimal removal rate achieved with minimal induced changes in the treated water's physical, chemical, and microbiological quality, and in line with WHO Guidelines for Drinking Water. The selection criteria for each eco-adsorbent/coagulant's treatment conditions were based on the minimum values that achieve results that comply with the WHO Guidelines for Drinking Water (WHO, 2017).

4.2. Water Treatment by Banana Peels

Two types of eco-adsorbents/coagulants made from banana peels: the raw banana peels and carbonized banana peels adsorbents were used to determine the removal of turbidity, pathogenic microorganisms, and trace metals from polluted water sources. The objective is to determine the dose that will optimally reduce those contaminants to provide safe drinking water with minimal resources.

4.2.1. Turbidity Removal

Three experimental settings were used to investigate the turbidity removal efficiency of the raw and the carbonized banana peels in low (27 NTU), medium (52 NTU), and high turbid (103 NTU) turbid water samples (the characteristics of the turbid water samples were presented earlier in table 3.2). Tables (4.1-4.6) show the characteristics of the turbid water samples (low, medium and high) treated with the raw banana peels and carbonized banana peels coagulants.

Table 4.1: Low Turbid Water Samples Treated by Raw Banana Peels

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	7	74%R	7.4	3%I	221	27%I	48.3	0%	4.5	0%
40	4	84%R	7.5	4%I	221	27%I	48.5	0.4%I	5	11%I
80	9	66%R	7.8	8%I	225	29%I	49	1.5%I	10	>100%I
160	11	60%R	7.9	10%I	226.3	30%I	49	1.5%I	27	>100%I

I: Increase, R: Reduction

320	14	50%R	8.1	13%I	227	30%I	49.1	2%I	53	>100%I
640	15	43%R	9.3	29%I	228	31%I	51	5%I	74	>100%I

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	12	77%R	6.8	6%R	230	15%I	47.5	3.1%R	5	4%R
40	11	78%R	6.9	4%R	230	15%I	47.5	3.1%R	7	35%I
80	11	79%R	7	3%R	231	16%I	48.6	0.8%R	15	>100%I
160	8	85%R	7.1	1.4%R	231	16%I	48.6	0.8%R	26	>100%I
320	8	85%R	7.3	1.4%I	234	17%I	49.3	0.6%I	55	>100%I
640	13	75%R	7.4	3.2%I	235	18%I	50.7	3.5%I	71	>100%I

Table 4.2: Moderate Turbid Water Samples Treated by Raw Banana Peels

I: Increase, R: Reduction

Table 4.3: High Turbid Water Samples Treated by Raw Banana Peels

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	4	96%R	7.1	2.74%R	311	0.2%I	48.3	2.4%R	4.5	21%R
40	9	91%R	7.1	2.05%R	313	0.8%I	49.2	0.6%R	10	75%I
80	10	90%R	7.2	2.74%R	314	1%I	49.2	0.6%R	25	>100%I
160	11	89%R	7.2	0.00	325	4.7%I	51	3%I	50	>100%I
320	12	88%R	7.2	0.00	327	5.3%I	52.3	5.6%I	79	>100%I
640	13	87%R	7.3	1.37%I	327	5.3%I	53	7%I	86	>100%I

I: Increase, R: Reduction

Table 4.4: Low Turbid Water Samples Treated by Carbonized Banana Peels

	Turbidity	pH	TDS	Alkalinity	Color

Dose (mg)	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	16	41%R	7.1	1.4%R	200	15%I	49.3	2.1%I	3	33%R
40	13	52%R	7.2	0%	201	15%I	49.3	2.1%I	4	11%R
80	10	63%R	7.2	0%	201	15%I	50.5	4.5%I	5	11%I
160	11	59%R	7.3	1.4%I	206	18%I	51	5.6%I	24	>100%I
320	14	48%R	7.3	1.4%I	207	19%I	51	5.6%I	31	>100%I
640	16	41%R	7.4	3%I	207	19%I	53	9.7%I	51	>100%I

I: Increase, R: Reduction

Table 4.5: Moderate Turbid Water Samples Treated by Carbonized Banana Peels

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	16	69%R	6.8	5.6%R	287	44%I	46	6%R	5	0%
40	14	73%R	6.9	4.2%R	287	44%I	46	6%R	5	0%
80	14	73%R	7.46	3.6%I	287	44%I	49.5	1%I	6	15%I
160	10	81%R	7.46	3.6%I	291	46%I	50.3	2.7%I	16	>100%I
320	10	81%R	7.7	7%I	291	46%I	52.1	6.3%I	46	>100%I
640	13	75%R	7.9	10%I	306	54%I	53.2	8.6%I	62	>100%I

I: Increase, R: Reduction

Table 4.6: High Turbid Water Samples Treated by Carbonized Banana Peels

	Turbidity	pH	TDS	Alkalinity	Color

I: Increase, R: Reduction

Dose (mg)	Level (NTU)	Change | (%) |	Leve l	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
										%R
										%R
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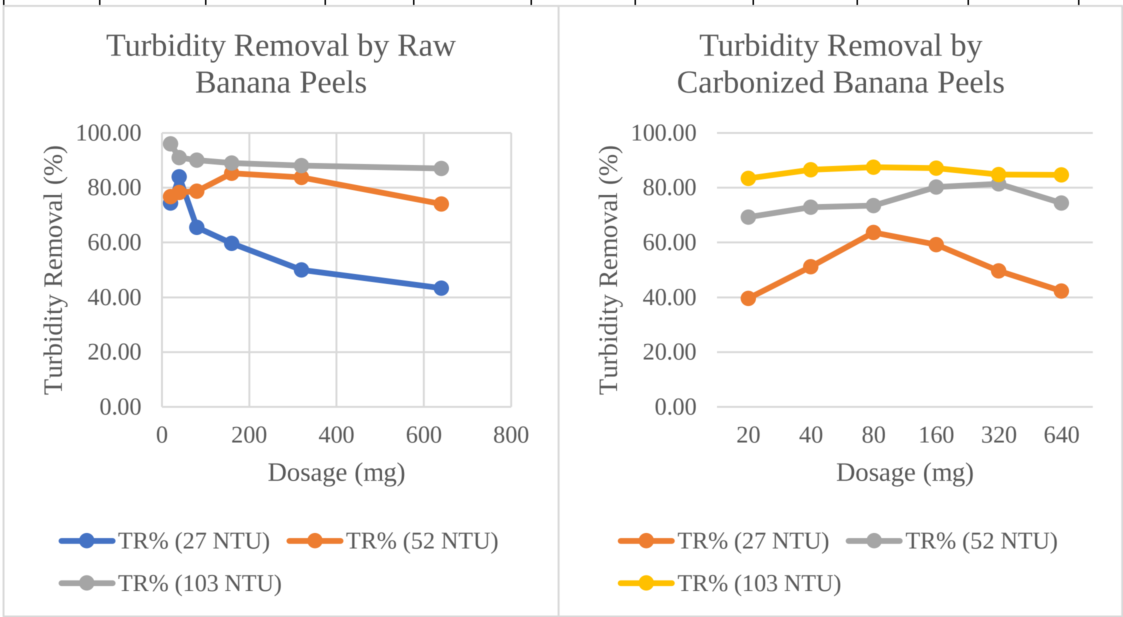


Figure 4.1: Percent Turbidity Removal at Various Banana Peels Dosages.
(a) Turbidity Removal by Raw Banana Peels (%). (b) Turbidity Removal by Carbonized Banana Peel. TR%: Turbidity Removal%.

To further summarize figure 4.1 illustrates turbidity removal for raw and carbonized banana peels coagulants in low, medium and high turbid water samples.

The highest percentage of turbidity removal was for the high turbid water sample treated with raw and carbonized banana peels coagulants. However, it is observed that when the banana peels coagulant was used without additional carbonization treatment, the highest turbidity removal rates were achieved at the lower dose ranges. Thus, the carbonization treatment did not influence the turbidity removal by banana peels. By interpreting the turbidity values shown in tables 4.1-4.6, acceptable levels that comply with the WHO Guideline Level (5 NTU) were achieved by raw banana peels only at the low and high levels using a coagulant dose of 40 mg and 20 mg. At those optimum doses, minimal changes were induced on the overall water quality parameters.

To further confirm that minimal changes affecting the water quality, figures 4.2-4.5 show the overall changes in the water Color, TDS, pH and Alkalinity at the different doses of the added banana peels coagulant.

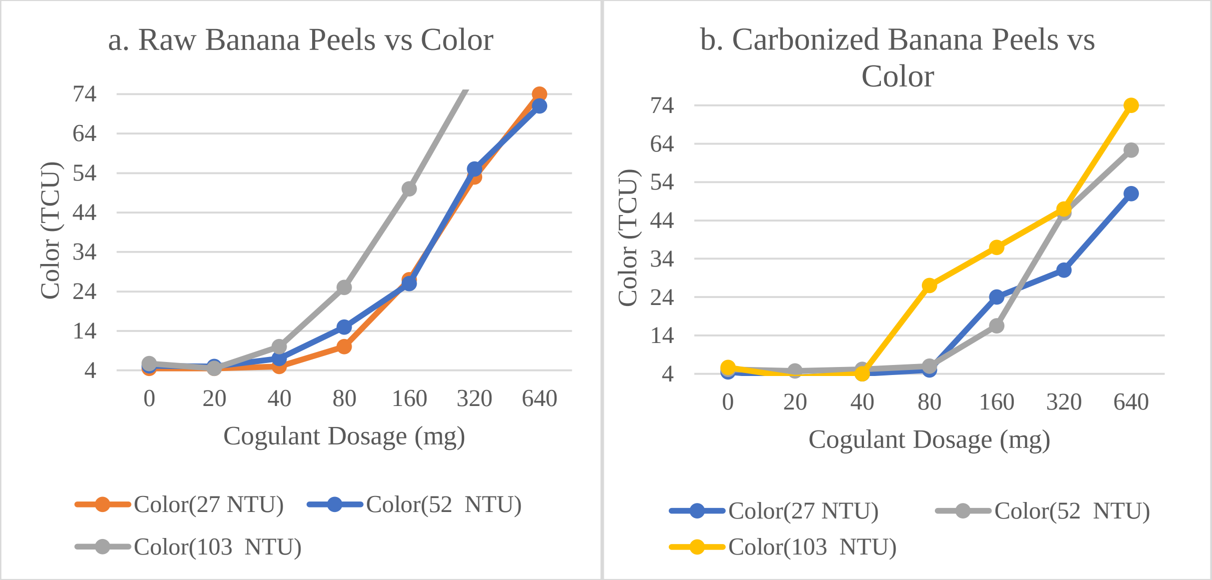


Figure 4.2: Effect of Banana Peels Dosage on Color (TCU).
(a) Raw Banana Peels vs Color. (b) Carbonized Banana Peels vs Color.

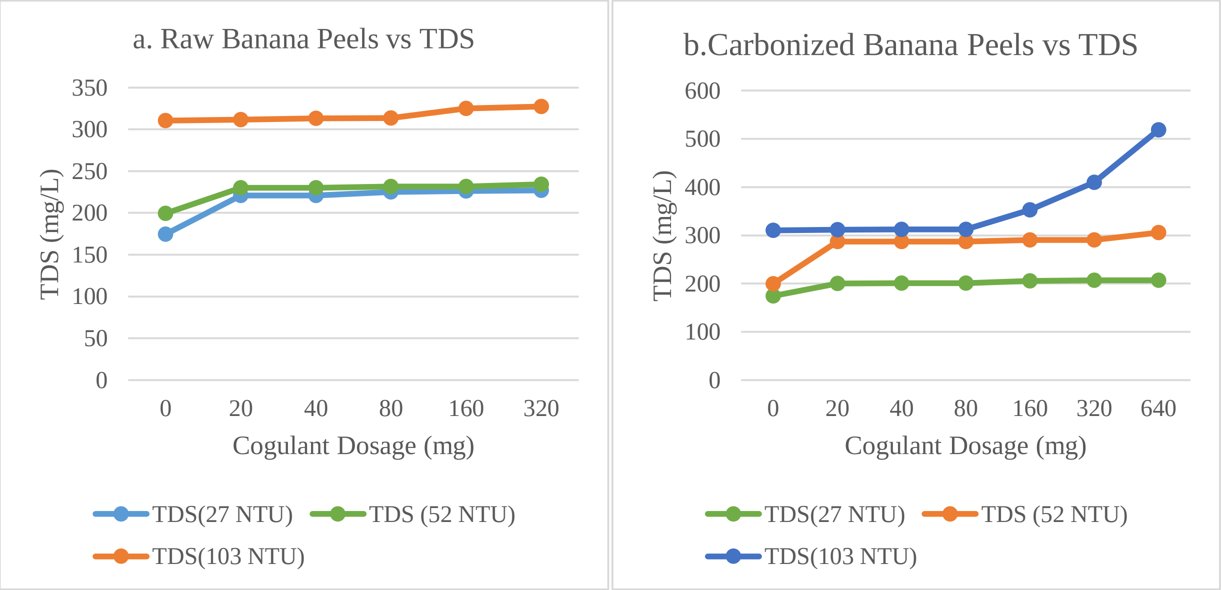


Figure 4.3: Effect of Banana Peels Dosage on TDS (mg/L).
(a) Raw Banana Peels vs TDS. (b) Carbonized Banana Peels vs TDS. TDS, Total Dissolved Solids.

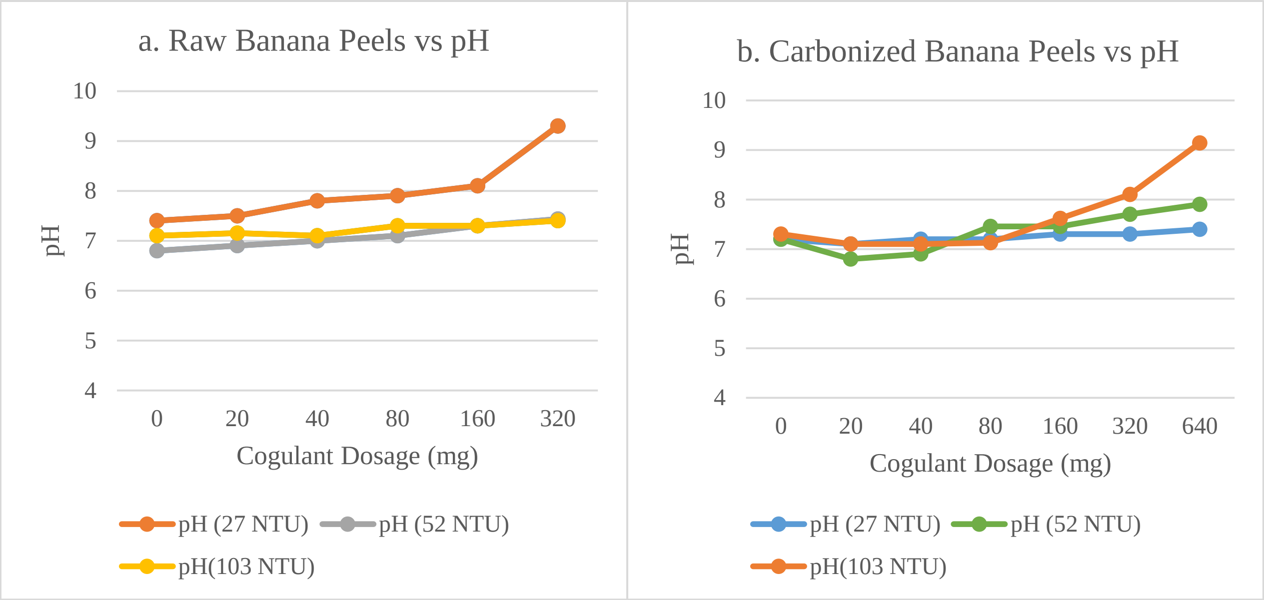


Figure 4.4: Effect of Banana Peels Dosage on pH.
(a) Raw Banana Peels vs pH. (b) Carbonized Banana Peels vs pH.

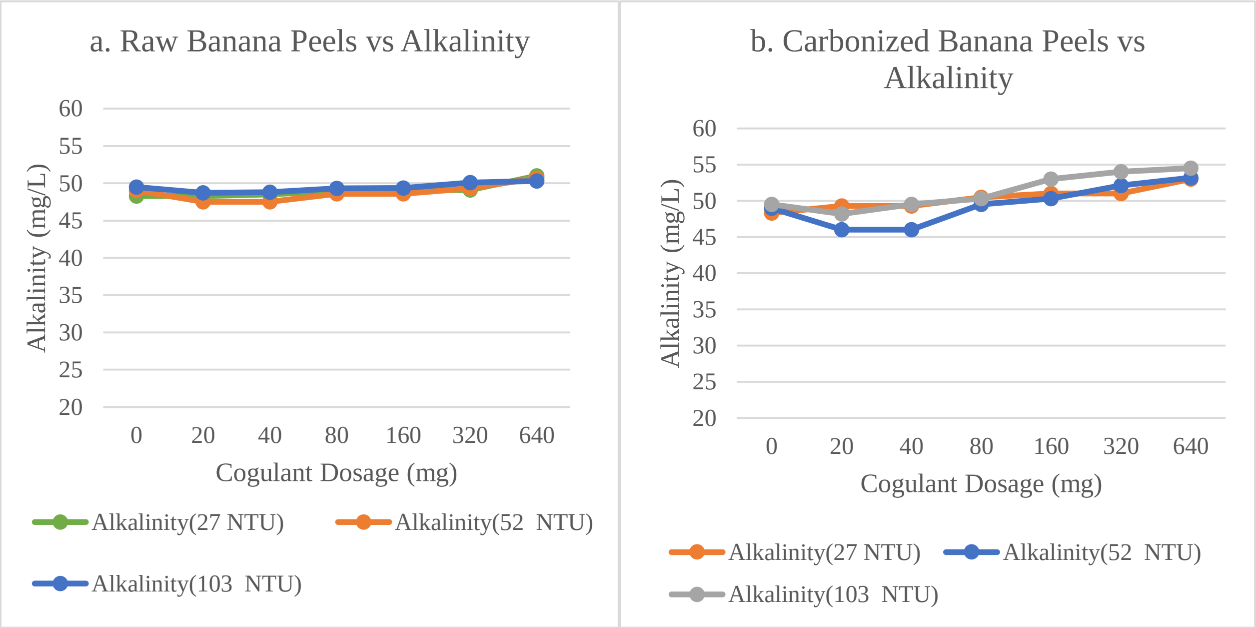


Figure 4.5: Effect of Banana Peels Dosage on Alkalinity (mg/L).
(a) Raw Banana Peels vs Alkalinity. (b) Carbonized Banana Peels vs Alkalinity

It can be observed from the illustrated figures that at the selected dose for turbidity removal, minimum changes in the overall water quality parameters were observed. Figures 4.2a, 4.3a, 4.4a, and 4.5a show that the color, TDS, pH, and alkalinity levels at the selected doses of the raw banana peels coagulant complied with the WHO Guidelines for Drinking Water. Accordingly, 40 and 20 mg of the raw banana peels were considered the optimal selected doses for the low and high turbid water samples. Further, the ANOVA test using Minitab 19 software was employed to observe the banana peels dosage (raw and carbonized) influence on the turbidity removal at a 90% confidence level.

Table 4.7: ANOVA. Analysis of Variance for Banana Peels Coagulant

a. ANOVA: TR% Versus Raw Banana Peels Dose (g)						**a. ANOVA: TR% Versus Carbonized Banana Peels Dose (g)**					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Source**	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Dose (g)	5	469.3	93.85	0.44	0.815	Dose (g)	5	297.5	59.50	0.18	0.967
Error	12	2579.5	214.96			Error	12	4070.9	339.24		
Total	17	3048.8				Total	17	4368.3			

ANOVA, Analysis of Variance. TR%, Turbidity Removal. DF, Total Degrees of Freedom. Adj SS, Adjusted Sums of Squares. Adj M, Adjusted Mean Squares. F-Value, Variation between Sample Means / Variation within the Samples. P-Value, Probability Value.

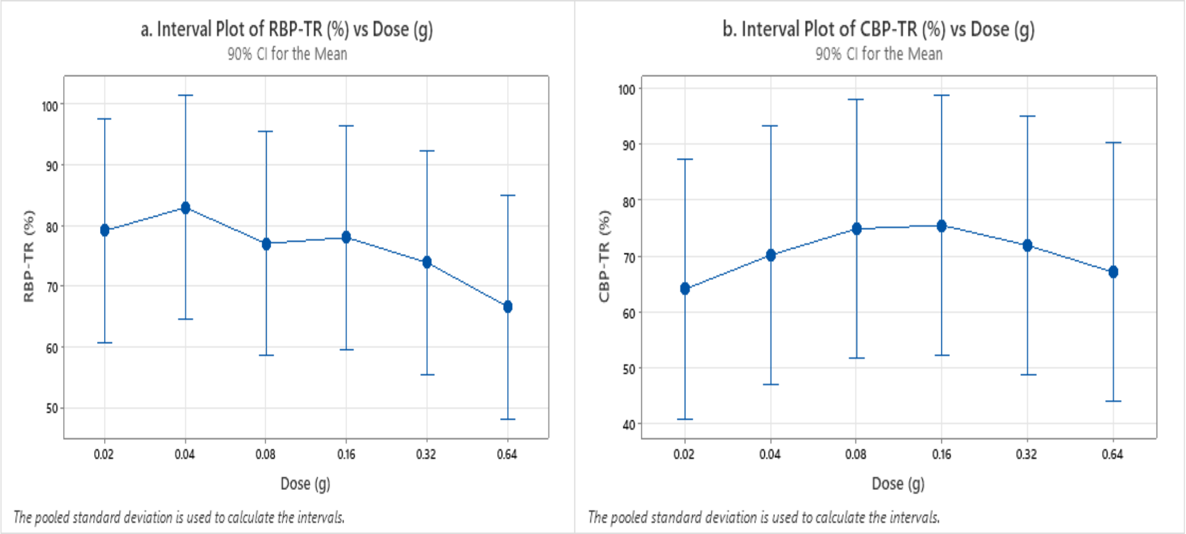


Figure 4.6: Interval Plot of Banana Peels Dose versus TR% at 90% CI.
(a) Interval Plot of Raw Banana Peels. (b) Interval Plot of Carbonized Banana Peels.
CI, Confidence Interval. TR%, Turbidity Removal

The ANOVA test illustrated by table 4.7 shows that increasing the banana peels coagulant dose is not correlated to higher turbidity removal rates. As such, the interval plots shown in figure 4.7 depict a non-linear correlation between the dosage of raw and carbonized banana peels coagulant and the turbidity removal. Moreover, the best dose for turbidity removal in the high turbid water sample was at the lowest range (20 mg) for this study, further confirming this non-linear relation. An earlier study by John et al. also showed that the maximum dose of the banana coagulant (1g/L) achieved the highest turbidity removal in the high turbid water sample of 160 NTU (John et al., 2017). Thus, it can be concluded that selecting the optimum dose for turbidity removal by the banana coagulants, as any other traditional coagulant, can be affected by the: operating conditions (input variables) of the coagulation process, initial turbidity levels, mixing speed, treatment time, and the physical-chemical characteristics of the water to be treated (Bartby, 2016; Haghiri et al., 2018).

4.2.2. Destruction of Pathogenic Microorganisms

Destruction of pathogenic microorganisms, specifically E. coli, was also studied using the banana peels treated extracts as presented in chapter 3. Figure 4.7 shows the microscopy images of the E. coli strains ATCC® 25922 colonies grown on nutrient agar plates with membrane filters and treated with the raw banana peels extract. Figures 4.8 and 4.9 show the microscopy images of the E. coli strains ATCC® 25922 colonies grown on nutrient agar plates with membrane filters and treated with the carbonized banana peels extract. Additionally, table 4.8 shows the percent reduction of E. coli colonies by the banana peels extract.

Table 4.8: Estimated Reduction of E. coli Count Samples by Banana Peels Extract.

Sample ID	Dose Concentration (mg/ml)	nC (colonies/10 ml)	nM (colonies/10 ml)	E. coli Reduction %
BR	20	205	ND	-
BC 1	2	136	N.D	-
BC 2	5	136	N.D	-
BC 3	10	136	73	46%
BC 4	20	290	108	63%

BR: Banana Raw, BC: Banana Carbonized, nC: number of colonies on the control plates with untreated membranes, nM: number of colonies on the plates with treated membranes, N.D: Not Detected, -: no reduction observed.

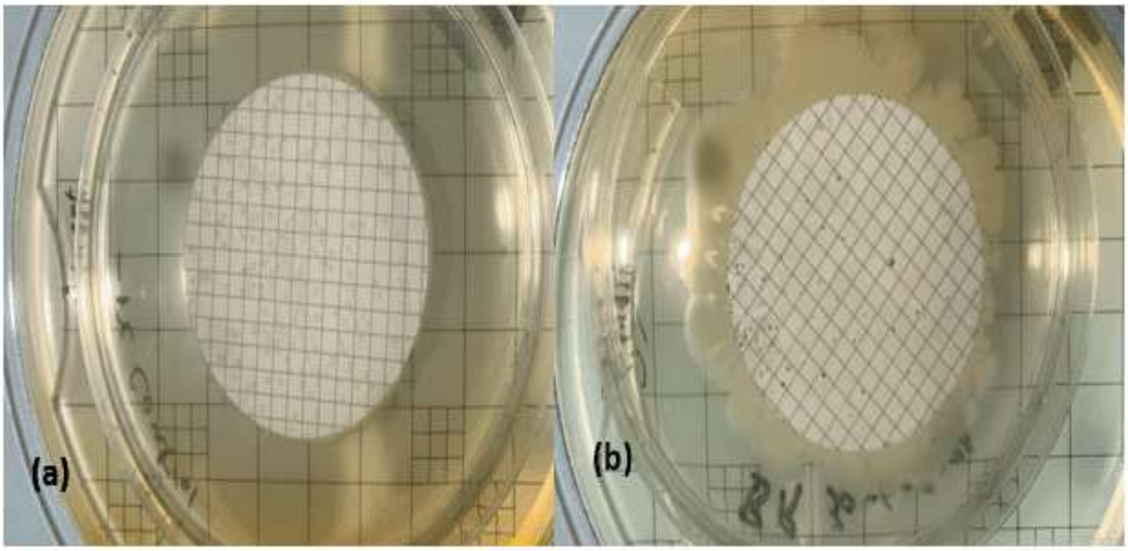


Figure 4.7: Reduction of E. coli in (a) Control Plate (b) Plate treated with Raw Banana Peels Extract (20 mg/ml)

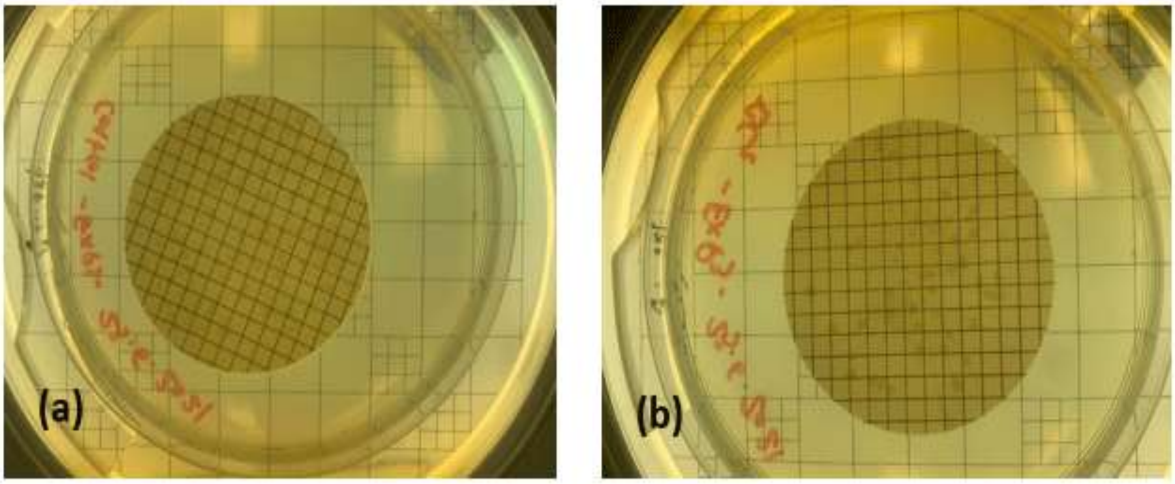


Figure 4.8: Reduction of E. coli in (a) Control Plate. (b) Plate treated with Carbonized Banana Peels Extract (10 mg/ ml)

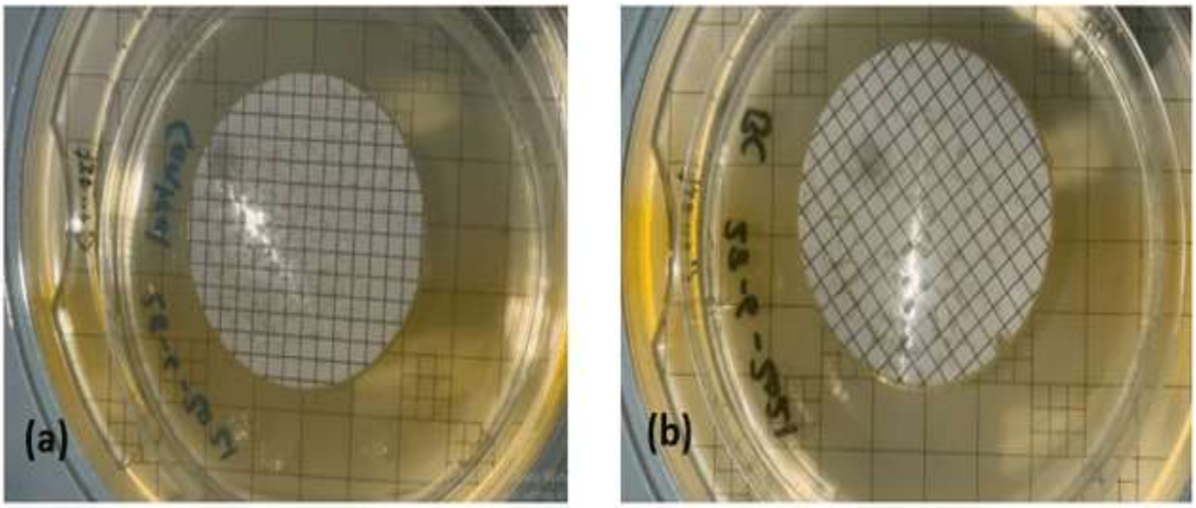


Figure 4.9: Reduction of E. coli in (a) Control Plate. (b) Plate treated with Carbonized Banana Peel Extract (20 mg/ ml)

Figure 4.7a shows the untreated negative control plate, and figure 4.7b shows the plate treated with 20 mg/ml raw banana peels extract. Moreover, figure 4.7b shows that bacterial growth was observed around the membrane filter, with no single colonies formed on the treated membrane filter. Still, it is hard to detect the effect of raw banana peels on microorganisms' destruction from this single experiment (Table 4.8). Thus, it might not be effective to use raw banana peels to reduce microbes without the supplementary use of water disinfection methods. However, experimenting with carbonized banana peels extract with a dose range of 2-20 mg/l showed that bacterial reduction was observed at 10 mg/ml dosage. This minimum dosage (10 mg/ml) of the carbonized banana peels showed a microbial reduction of about 46%, as indicated in table 4.8. The preliminary results showed that the E. coli reduction could be further enhanced by increasing the dose to 20 mg/ml leading to a 63% reduction in E. coli (Table 4.8). Therefore, this preliminary experimentation presents a better potential for carbonized banana peels in the reduction of microbes. Still, additional and follow-up studies are needed with more data and modeling designs to document possible carbonized banana peels' antibacterial properties.

4.2.3. Heavy Metals Removal

The removal of trace metals of chromium and lead ions by banana peels' adsorbents was also experimented. The purpose is to identify the optimum conditions, adsorbent dose, and contact time, achieving the best results for heavy metals removal with minimal resources. The removal rates of chromium and lead and the adsorption capacity performed by the banana peel adsorbents were calculated using the Removal Rate (R %) and Adsorption Capacity (q_e) equations presented in chapter 3. Using the calculated data, the raw and carbonized banana peels adsorbents' statistical analysis was interpreted by the Analysis of Variance (ANOVA), Pareto charts, and normal probability plots using the factorial regression analysis at 95% confidence level by Minitab 19 software. Table 4.9 illustrates the ANOVA computed for the chromium and lead removal by the banana peels adsorbents. The Pareto charts presented in figure 4.10 shows the effects of the design factors of adsorbent dose (AD), contact time (CT), and chromium and lead concentration (HMC) on the chromium and lead removal efficiency. Additionally, figure 4.11 shows the normal probability plots for the chromium and lead removal.

It can be inferred from table 4.9a that both the adsorbent dose (AD) and contact time (CT) are statistically significant for chromium removal by the raw banana peels adsorbent. At the same time, the chromium and lead concentrations are statistically insignificant since P-value>0.05. On the other hand, table 4.4b shows that the adsorbent dose, contact time, chromium, and lead concentration are statistically significant to the lead removal rate. Additionally, the Pareto charts shown in figure 4.10a indicates that the contact time has significantly influenced chromium removal, followed by the adsorbent dose. While, the Pareto chart in figure 4.10b shows that the most statistically significant factor for lead removal was the contact time, followed by the chromium and lead concentrations and the adsorbent dose. As such, the normality evidence has been satisfied since P-value> 0.05, as shown in figures 4.11a-b. On the other hand, the carbonization treatment of the banana peels adsorbent exhibited different chromium and lead removal conditions. Table 4.9c and table 4.9 d confirm that the chromium and lead concentrations were statistically significant for chromium and lead removal by the carbonized banana peels. At the same time, the adsorbent dose and contact time were not statistically significant. The Pareto charts in figures 4.10c and 4.10d show that the chromium and lead concentrations exhibited the most critical influence on chromium and lead removal rates. As such, the normality evidence has been satisfied as demonstrated by figure 4.11c-d since P-value> 0.05.

Table 4.9: ANOVA for Lead and Chromium Removal by Banana Peels. (a) ANOVA for R% (Cr) _RBP. (b) ANOVA for R% (Pb) _RBP. (c) ANOVA for R% (Cr) _CBP. (d) ANOVA for R% (Pb) _CBP.

(a) ANOVA for R%(Cr)_ RBP						**(b) ANOVA for R%(Pb)_ RBP**					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Source**	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	4	2.18102	0.54526	70.22	0.000	**Model**	4	7468.13	1867.03	840.66	0.000
Linear	3	0.35505	0.11835	15.24	0.000	**Linear**	3	2313.30	771.10	347.20	0.000
AD	1	0.09396	0.09396	12.10	0.005	**AD**	1	179.89	179.89	81.00	0.000
HMC	1	0.00442	0.00442	0.57	0.466	**HMC**	1	692.07	692.07	311.62	0.000
CT	1	0.25666	0.25666	33.06	0.000	**CT**	1	1441.35	1441.35	648.99	0.000
Curvature	1	1.82598	1.82598	235.16	0.000	**Curvature**	1	5154.83	5154.83	2321.05	0.000
Error	11	0.08541	0.00776			**Error**	11	24.43	2.22		
Lack-of-Fit	4	0.05409	0.01352	3.02	0.096	**Lack-of-Fit**	4	2.09	0.52	0.16	0.950
Pure Error	7	0.03132	0.00447			**Pure Error**	7	22.34	3.19		
Total	15	2.26643				**Total**	15	7492.56			
(c) ANOVA for R%(Cr)_ CBP						**(d) ANOVA for R%(Pb)_ CBP**					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Source**	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	4	2.59272	0.64818	115.13	0.000	**Model**	4	9519.22	2379.80	286.26	0.000
Linear	3	0.12324	0.04108	7.30	0.006	**Linear**	3	426.48	142.16	17.10	0.000
AD	1	0.02100	0.02100	3.73	0.080	**AD**	1	11.34	11.34	1.36	0.268
HMC	1	0.08752	0.08752	15.54	0.002	**HMC**	1	414.06	414.06	49.81	0.000
CT	1	0.01473	0.01473	2.62	0.134	**CT**	1	1.09	1.09	0.13	0.725
Curvature	1	2.46948	2.46948	438.62	0.000	**Curvature**	1	9092.73	9092.73	1093.75	0.000
Error	11	0.06193	0.00563			**Error**	11	91.45	8.31		
Lack-of-Fit	4	0.04333	0.01083	4.08	0.051	**Lack-of-Fit**	4	59.47	14.87	3.25	0.083
Pure Error	7	0.01860	0.00266			**Pure Error**	7	31.98	4.57		
Total	15	2.65465				**Total**	15	9610.66			

ANOVA, Analysis of Variance. TR%, Turbidity Removal. DF, Total Degrees of Freedom. Adj SS, Adjusted Sums of Squares. Adj M, Adjusted Mean Squares. F-Value, Variation between Sample Means / Variation within the Samples. P-Value, Probability

Value. AD, Adsorbent Dose, HMC, Chromium and Lead Concentration. CT, Contact Time.

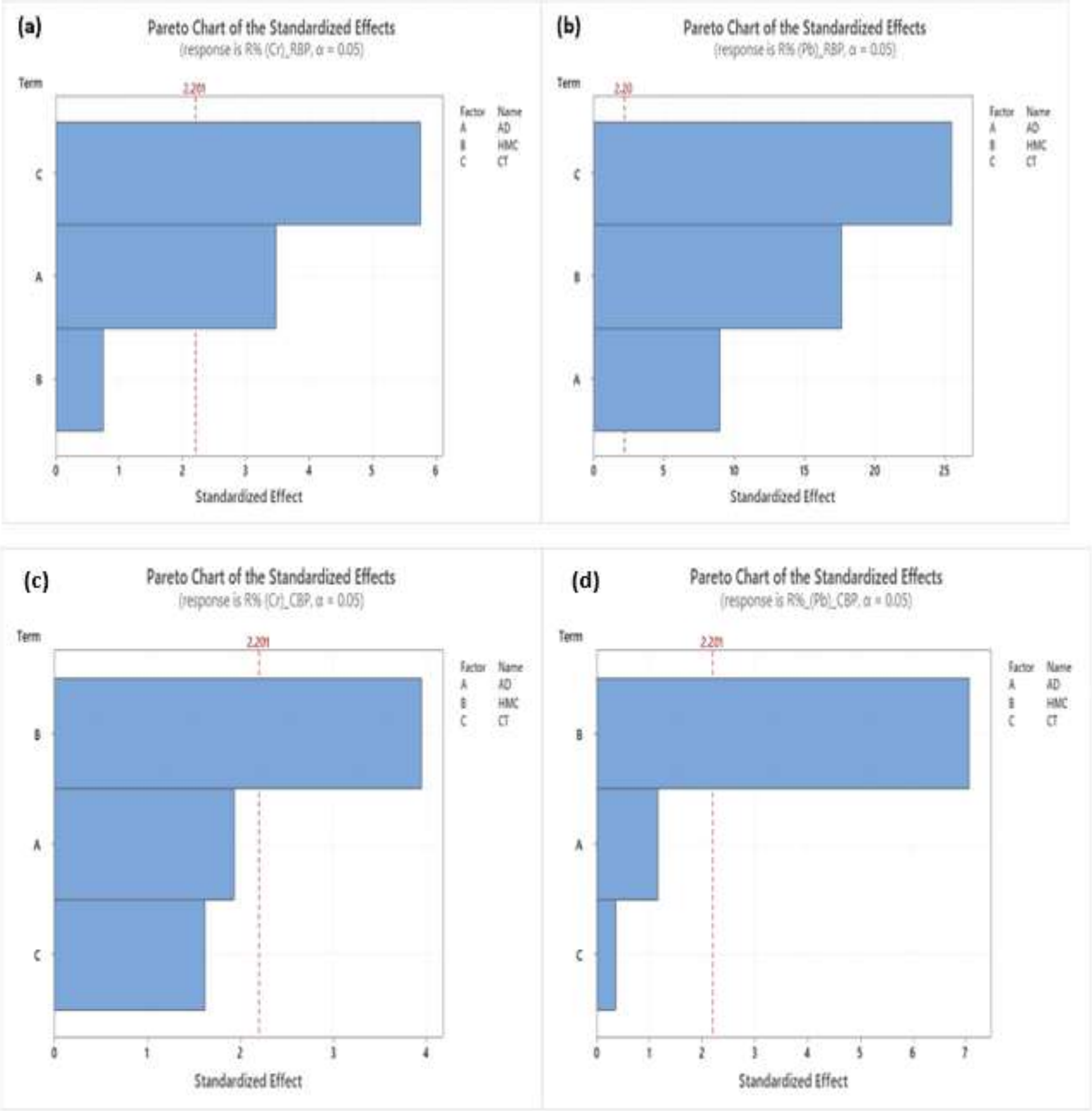


Figure 4.10: Banana Peels Pareto Charts.
(a) Pareto Chart for R % (Cr) _RBP. (b) Pareto Chart for R % (Pb)_RBP. (c) Pareto Chart for R % (Cr) _CBP. (d) Pareto Chart for R % (Pb)_CBP. R % (Cr) _RBP: Chromium Removal Rate for Raw Banana Peels. R % (Pb)_RBP: Lead Removal Rate for Raw Banana Peels. R % (Cr) _CBP: Chromium Removal Rate for Carbonized Banana Peels. R % (Pb)_CBP: Lead Removal Rate for Carbonized Banana Peels AD: adsorbent dose, mg. HMC: Chromium and Lead Concentration, mg/L. CT: Contact Time, minutes.

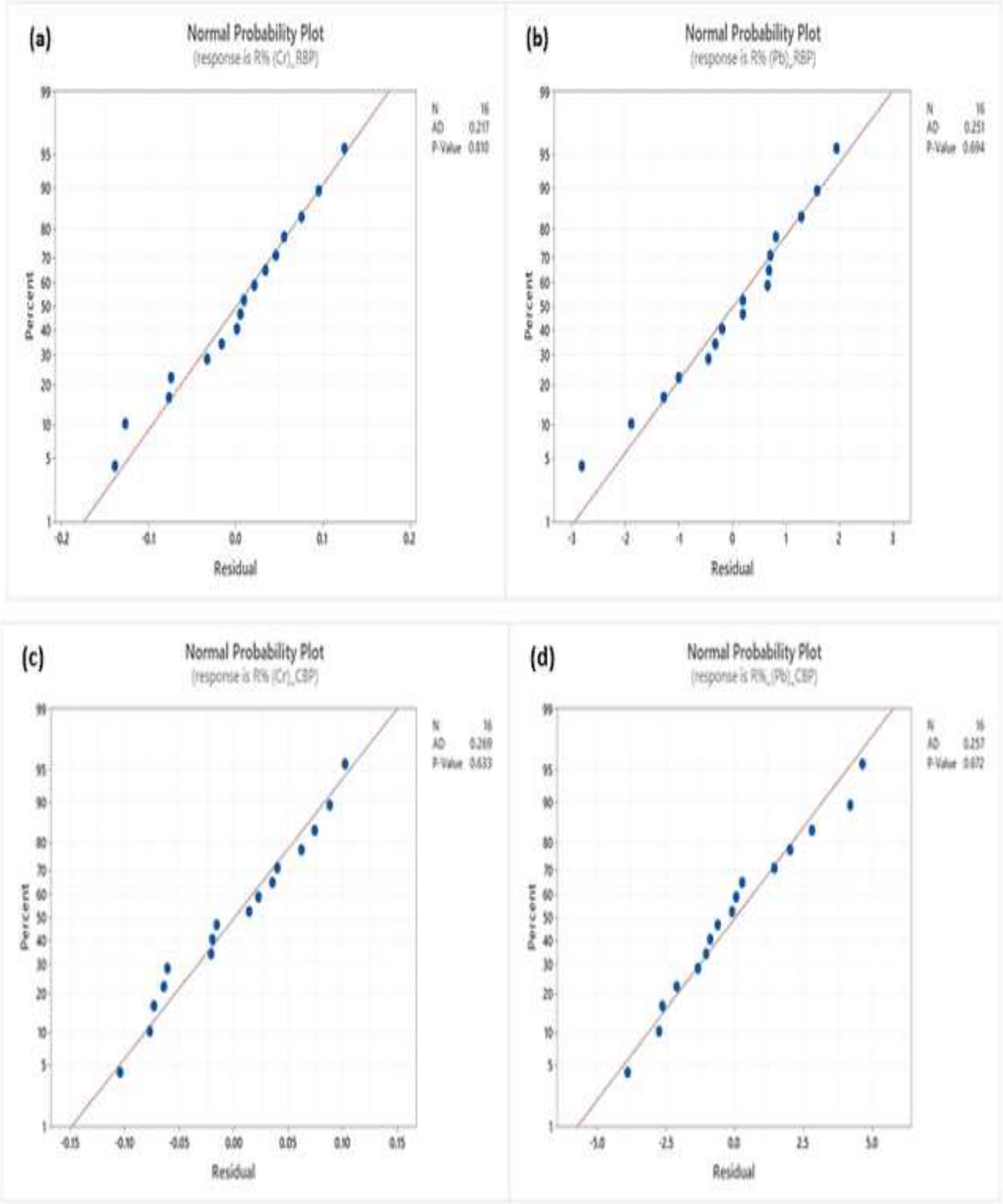
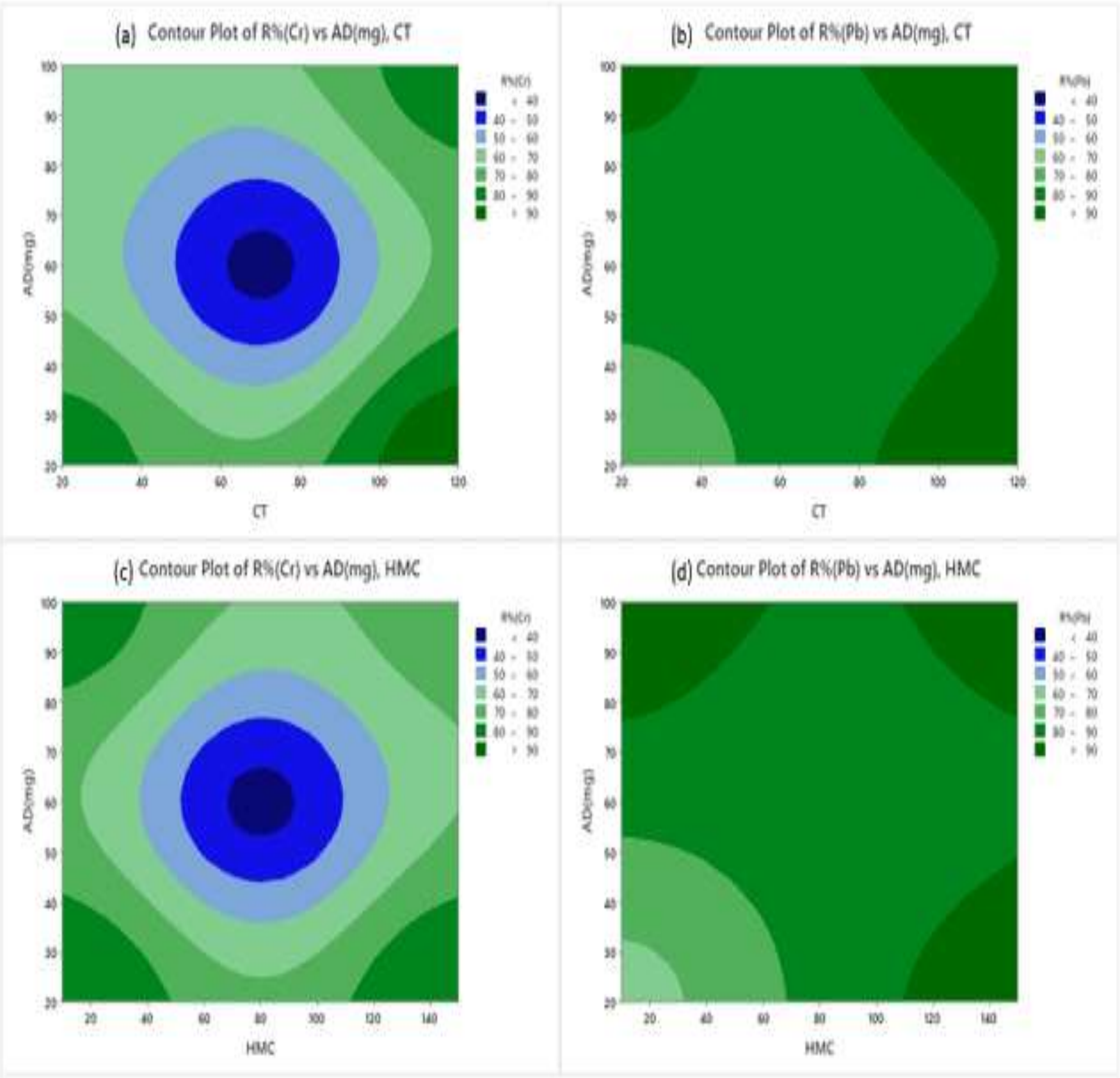


Figure 4.11: Banana Peels Normal Probability Plots.
(a) Normal Probability Plot for R% (Cr) _RBP. (b) Normal Probability Plot for R% (Pb) _RBP. (c) Normal Probability Plot for R% (Cr)_CBP. (d) Normal Probability Plot for R% (Pb) _CBP. R % (Cr) _RBP: Chromium Removal Rate for Raw Banana Peels. R % (Pb) _RBP: Lead Removal Rate for Raw Banana Peels. R % (Cr) _CBP: Chromium Removal Rate for Carbonized Banana Peels. R % (Pb) CBP: Lead Removal Rate for Carbonized Banana Peels. AD: Anderson-Darling

Hence, it can be concluded from the statistical analysis of this preliminary study that the removal rates of chromium and lead depend on several factors such as the adsorbent dose, contact time, and heavy metals concentration. The studies presented in chapter 2 also report that heavy metals adsorption and removal efficiency can vary based on a combination of factors such as the: pH of the adsorbent, adsorbent dose, contact time, heavy metals concentration, and the physio-chemical characteristics of the water or wastewater sample (Arunakumara, 2013; Lenog, 2018). Thus, selecting optimum chromium and lead removal settings depends on the combination of the variables indicated, which can also reflect whether the carbonized form of banana peels adsorbent would improve the chromium and lead removal rates. As such, the contour plots shown below in figures 4.12 and 4.13 were used to define high chromium and lead removal outcomes at the lowest possible dose. The produced contour lines in figures 4.12 and 4.13 display different points that have the same response. The darkest green regions represent the adsorbent dose, contact time, chromium and, lead concentrations at the highest outcome values, as follow:



(a) Contour Plot of R%(Cr) vs AD(mg), CT

(b) Contour Plot of R%(Pb) vs AD(mg), CT

(c) Contour Plot of R%(Cr) vs AD(mg), HMC

(d) Contour Plot of R%(Pb) vs AD(mg), HMC

Figure 4.12: Contour Plots of Raw Banana Peels.
(a) Contour Plot of R %(Cr) vs. AD, CT. (b) Contour Plot of R %(Pb) vs AD, CT. (c) Contour Plot of R%(Cr) vs. AD, HMC. (d) Contour Plot of R %(Pb) vs. AD, HMC. R% (Cr): Chromium Removal Rate. R %(Pb): Lead Removal Rate. AD: Adsorbent Dose, mg. HMC: Chromium and Lead

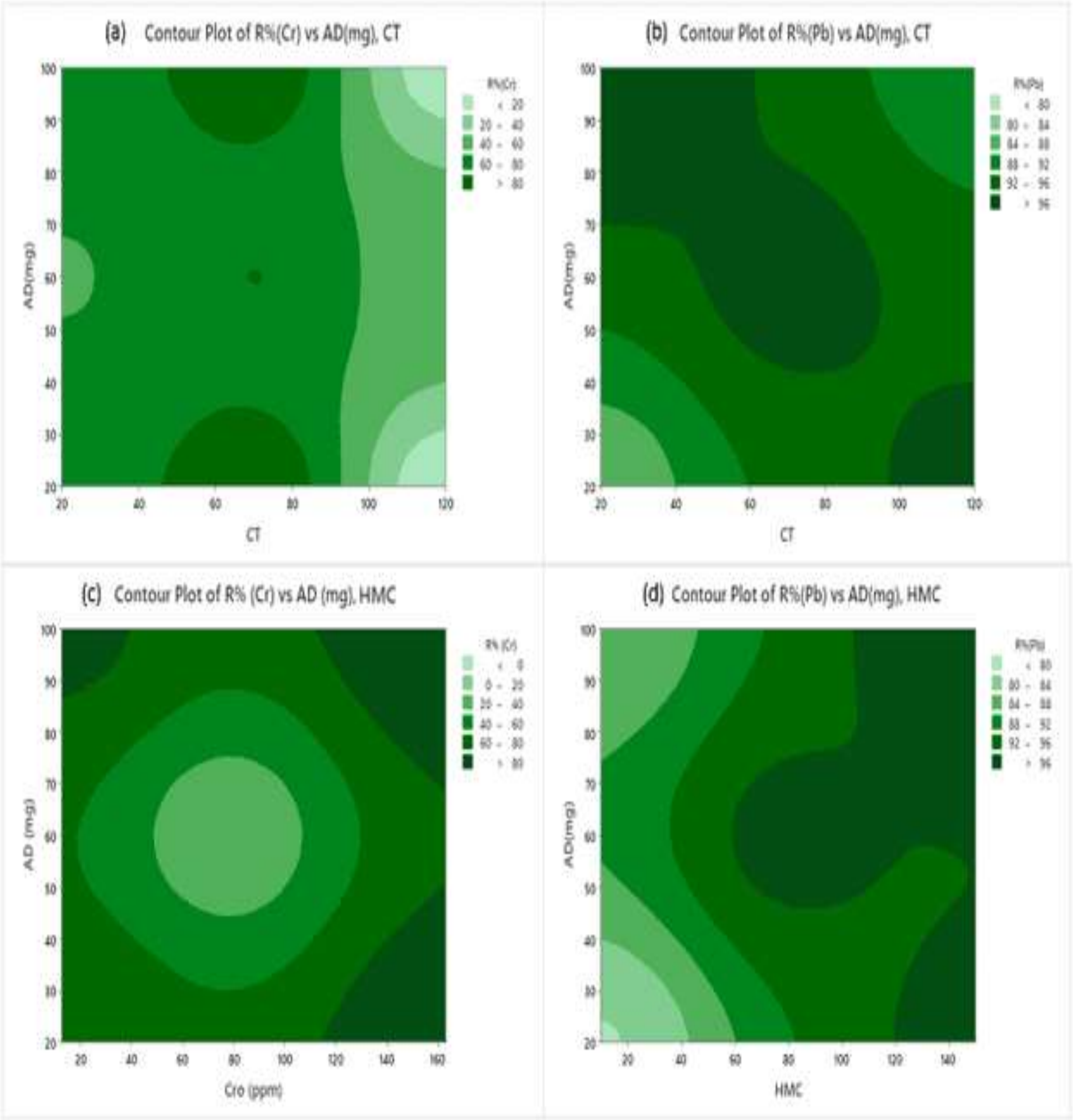


Figure 4.13: Contour Plots of Carbonized Banana Peels.
(a) Contour Plot of R %(Cr) vs. AD, CT. (b) Contour Plot of R %(Pb) vs. AD, CT. (c) Contour Plot of R%(Cr) vs. AD, HMC. (d) Contour Plot of R %(Pb) vs. AD, HMC. R% (Cr): Chromium Removal Rate. R %(Pb): Lead Removal Rate. AD: Adsorbent Dose, mg. HMC: Chromium and Lead concentration, ppm

By interpreting figures 4.12 and 4.13, it can be noted that selecting the lowest adsorbent dose of 20 mg for the raw and carbonized banana peels can achieve high chromium and lead removal outcomes. In fact, the heavy metals removal rates can gradually decrease at high doses of the banana peels adsorbent, which can be explained by the availability of the active binding sites, as reported in earlier studies (Anwar et al., 2012). However, the contour plots show that the efficient chromium and lead removal rates achieved at 20 mg adsorbent dose depend on the associated contact time and heavy metals concentration. On the other hand, the WHO Guidelines for Drinking Water specifies that the chromium level should not exceed 0.05 mg/L and the lead level should not exceed 0.01 mg/L. This would require achieving at least a 99.75% chromium removal rate and a 99.95% lead removal rate based on the generated data of this study. However, the presented contour plots created are based on Minitab's 19 estimations of the associated model for the experimental design, which might not show the complete picture of the optimum conditions, especially when considering random and systematic experimental errors for the outcomes of the model. Hence, the values obtained from the contour plots interpretation can't be taken for granted to reach the desirable chromium and lead removal rates for drinking water purposes. Nevertheless, the contour plots helped to determine desirable chromium and lead removal rates by the banana peel adsorbents at a lower contact time and adsorbent dose ranges, which need to be re-considered and optimized in follow-up studies.

Hence, for this pilot study, the optimum conditions for chromium and lead removal by the raw and carbonized banana peels were computed by the Minitab 10 Response Optimizer of the factorial DOE. Tables 4.10 and 4.11 show the optimum treatment conditions obtained from figures 4.14 and 4.15, which achieved the highest chromium and lead removal rates by the banana peels adsorbents complying with the WHO Guidelines for Drinking Water.

Table 4.10: Optimum Conditions for Chromium and Lead Removal by the Raw Banana Peels Adsorbent.

Optimum Conditions for Chromium and Lead Removal by Raw Banana Peels			
Chromium Removal, R(Cr)%		Lead Removal, R(Pb)%	
Optimum adsorbent dose, mg	20	Optimum adsorbent dose, mg	20
Optimum contact time, min	120	Optimum contact time, min	120
Optimum initial chromium concentration, mg/L	10	Optimum initial lead concentration, mg/L	150
R(Cr%)	99.75%	R(Pb%)	99.95%

Table 4.11: Optimum Conditions for Chromium and Lead Removal by Carbonized Banana Peels Adsorbent.

Optimum Conditions for Chromium and Lead Removal by Carbonized Banana Peels			
Chromium Removal, R(Cr)%		Lead Removal, R(Pb)%	
Optimum adsorbent dose, mg	100	Optimum adsorbent dose, mg	100
Optimum contact time, min	120	Optimum contact time, min	20
Optimum initial chromium concentration, mg/L	150	Optimum initial lead concentration, mg/L	150
R(Cr%)	99.75%	R(Pb%)	99.95%

It can be deduced from Table 4.10 that the banana peels adsorbent achieved desirable lead removal rates at a low dose without the need for further treatment. On the other hand, the desirable chromium removal was obtained at a low dose for water with low chromium concentrations. Table 4.11 shows that the carbonized form of the banana peels adsorbent had the advantage of chromium removal from water solutions with higher chromium concentration levels. Thus, enhancing the banana peels adsorbent with the carbonization treatment for situations requiring treating highly contaminated water with chromium levels would be favorable. However, the optimum contact time was at the highest range except for lead treatment by carbonized banana peels. A follow-up study would seek to reduce the optimum contact time to enhance treatment under emergency conditions. An earlier reported study in 2013 also discussed that the optimum contact time varies depending on the heavy metals levels and the physical-chemical characteristics of the polluted water sample (Arunakumara et al., 2013). Additionally, the adsorption of metal ions gradually decreases with time after equilibrium, so expanding the contact time range would be beneficial in follow-up studies to detect the equilibrium stage where adsorption of metal ions is maximum, as presented by before (Hossain et al., 2012; Arunakumara, 2013). Thus, it can be concluded that the optimum conditions for chromium and lead removal for water treatment for domestic purposes would vary depending on the treatment conditions and the other presented factors.

4.2.4. Efficiency of Banana Peels for Contaminants Removal in Water Treatment

Table 4.12 shows the input variables: the banana peels dose, contact time, initial contaminant concentration (chromium, lead, turbidity, and E. coli), and the corresponding output variables (chromium removal rate, lead removal rate, turbidity removal, and E. coli reduction rate). As indicated before, the input variables were selected based on the outputs of the lowest possible level that did not exceed the WHO Guidelines for Drinking Water (WHO, 2017).

Table 4.12: Banana Peels Overall Profile in Enhancing Water Quality and Safety

<table>
<tr><td colspan="6">Chromium Removal</td></tr>
<tr><td colspan="4">Input Variables</td><td colspan="2">Output Variables</td></tr>
<tr><td>Adsorbent dose (mg)</td><td colspan="2">Contact time (min)</td><td>Chromium Level (mg/L)</td><td>R (Cr%)</td><td>Cre, mg/L</td></tr>
<tr><td colspan="6">A. Raw Banana Peels</td></tr>
<tr><td>20</td><td colspan="2">120</td><td>10</td><td>99.75%</td><td>0.05</td></tr>
<tr><td colspan="4">Compliance with WHO Guidelines for Drinking Water for chromium (0.05 mg/L)</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">B. Carbonized Banana Peels</td></tr>
<tr><td>100</td><td colspan="2">120</td><td>150</td><td>99.75%</td><td>0.05</td></tr>
<tr><td colspan="4">Compliance with WHO Guidelines for Drinking Water for chromium (0.05 mg/L)</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">Lead Removal</td></tr>
<tr><td colspan="4">Input Variables</td><td colspan="2">Output Variables</td></tr>
<tr><td>Adsorbent dose (mg)</td><td colspan="2">Contact time (min)</td><td>Lead Level (mg/L)</td><td>R (Pb%)</td><td>Pbe, mg/L</td></tr>
<tr><td colspan="6">A. Raw Banana Peels</td></tr>
<tr><td>20</td><td colspan="2">120</td><td>150</td><td>99.95%</td><td>0.01</td></tr>
<tr><td colspan="4">Compliance with WHO Guidelines for Drinking Water for lead (0.01 mg/L)</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">B. Carbonized Banana Peels</td></tr>
<tr><td>100</td><td colspan="2">20</td><td>150</td><td>99.95%</td><td>0.01</td></tr>
<tr><td colspan="4">Compliance with WHO Guidelines for Drinking Water for lead (0.01 mg/L)</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">Turbidity Removal</td></tr>
<tr><td colspan="4">Input Variables</td><td colspan="2">Output Variables</td></tr>
<tr><td rowspan="2">Adsorbent dose (mg)</td><td colspan="2">Contact time (min)</td><td rowspan="2">Initial Turbidity (NTU)</td><td rowspan="2">TR (%) Turbidity removal rate</td><td rowspan="2">Final Turbidity (NTU)</td></tr>
<tr><td>Mixing time</td><td>Settling time</td></tr>
<tr><td colspan="6">Raw Banana Peels</td></tr>
<tr><td>40</td><td>20</td><td>20</td><td>27</td><td>84%</td><td>4</td></tr>
<tr><td>20</td><td>20</td><td>20</td><td>103</td><td>96%</td><td>4</td></tr>
<tr><td colspan="4">Compliance with WHO Guidelines for Drinking Water for turbidity (5 NTU)</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">Overall Induced Changes in the Water Quality</td></tr>
<tr><td colspan="6">A. Low Turbid Water Treatment by 40 mg Raw Banana Coagulant</td></tr>
<tr><td colspan="4">Color (TCU): 5</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">Total Dissolved Solids (mg/L): 221</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">pH: 7.5</td><td colspan="2">Comply</td></tr>
</table>

Alkalinity (mg/L): 48.5				Comply
B. High Turbid Water Treatment by 20 mg Raw Banana Coagulant				
Color (TCU): 4				Comply
Total Dissolved Solids (mg/L): 312				Comply
pH: 7.1				Comply
Alkalinity (mg/L): 48.3				Comply
E. coli Reduction				
Input Variables				**Output Variables**
Adsorbent dose (mg)	**Contact time (min)**	**Initial E. coli count (colonies/ 10 ml)**	**E. coli Reduction %**	**Final E. coli count (colonies/ 10 ml)**
Carbonized Banana Peels				
200	30	290	63	108
Compliance with WHO Guidelines for Drinking Water (0)				Does not comply

R (Cr %), Chromium Removal Rate %. R (Pb %), Lead Removal Rate %.
TR%, Turbidity Removal Rate %. NTU, Nephelometric Turbidity Unit. TCU, True Color Units.

Hence, based on table 4.12, the use of raw banana peels was effective in chromium and lead removal, and the use of the carbonized form would be more effective for high level contamination with chromium. However, the raw banana peels acted as a better coagulant for turbidity removal than in the carbonized form. In addition, the selected dose for turbidity removal barely induced minimal changes to the overall physical-chemical water quality parameters, which complied with the WHO Guidelines for Drinking Water. Still, the raw banana peels coagulant was not effective in the destruction of pathogens. And, although carbonization enhanced the E. coli reduction, it did not remove it completely to the level of no E. coli detection (WHO, 2017). Additional studies are needed to optimize the disinfecting capacity of the banana peels adsorbent, and a follow-up study need more data and modeling designs to possibly improve the overall performance of banana peels eco-adsorbents/coagulants.

4.3. Water Treatment by Eggshells

Similar to the banana peels, two types of eco-adsorbents/coagulants made from eggshells waste: the raw and carbonized eggshells adsorbents, were used for turbidity removal, reduction of pathogenic microorganisms, and trace metals removal from polluted water sources. The objective was to determine the eco-adsorbent/ coagulant dose to optimally reduce those contaminants to provide safe drinking water with minimal resources.

4.3.1. Turbidity Removal

As banana peels products, the turbidity removal efficiency of the raw and carbonized eggshells was investigated using low, medium, and high turbid water samples. Tables (4.13-4.18) show the characteristics of the turbid water samples (low, medium, and high) treated with raw and carbonized eggshells coagulants.

Table 4.13: Low Turbid Water Samples Treated by Raw Eggshells

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	17	37%R	6.8	5.6%R	183	4%I	49.8	3.1%I	4.5	0%
40	17	37%R	6.8	5.6%R	183	5%I	50.1	3.7%I	6.5	44.4%I
80	22	19%R	7	2.8%R	185	6%I	50.3	4.1%I	12	>100%I
160	22	19%R	7	2.8%R	187	7%I	51	5.6%I	18	>100%I
320	23	15%R	7	2.8%R	191	10%I	52	7.7%I	23	>100%I
640	24	11%R	7	2.8%R	198	13%I	53	9.7%I	50	>100%I

I: Increase, R: Reduction

Table 4.14: Moderate Turbid Water Samples Treated by Raw Eggshells

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	35	33%R	6.9	4.2%R	215	9%I	50.3	2.7%I	5	4%R
40	33	36%R	6.9	4.2%R	225	13%I	50.5	3.1%I	5	4%R
80	31	40%R	7	3%R	311	56%I	51.1	4.3%I	5	4%R
160	19	63%R	7.02	2.5%R	315	58%I	51.1	4.3%I	6	15%I
320	30	43%R	7.1	1.4%R	318	59%I	53.1	8.4%I	6	15%I
640	33	37%R	7.1	1.4%R	318	59%I	54.7	11.6%I	8	54%I

I: Increase, R: Reduction

Table 4.15: High Turbid Water Samples Treated by Raw Eggshells

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	50	51%R	6.9	5.5%R	339	9%I	46	7.3%R	4	30%R
40	40	61%R	6.9	5.5%R	339	9%I	46	6.9%R	4	30%R
80	35	66%R	6.9	5.5%R	339	9%I	46.5	6.1%R	4	30%R
160	26	74%R	7.1	2.7%R	341	10%I	48.4	2.2%R	4	30%R
320	40	61%R	7.2	1.2%R	345	11%I	51	3%I	4	30%R
640	42	59%R	7.2	1.2%R	357	15%I	52.3	5.7%I	5	15%R

I: Increase, R: Reduction

Table 4.16: Low Turbid Water Samples Treated by Carbonized Eggshells

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	14	48%R	7.1	1.4%R	200	15%I	49.3	2.1%I	3	33%R
40	5	81%R	7.2	0%	200	15%I	49.3	2.1%I	4	11%R
80	10	63%R	7.2	0%	200	15%I	51	5.6%I	5	11%I
160	13	52%R	7.2	0%	206	18%I	51	5.6%I	24	>100%I
320	14	48%R	7.3	1.4%I	210	20%I	51	5.6%I	27	>100%I
640	16	41%R	7.4	2.8%I	210	20%I	52	7.7%I	50	>100%I

I: Increase, R: Reduction

Table 4.17: Moderate Turbid Water Samples Treated by Carbonized Eggshells

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	19	63%R	7.2	0%	286	43%I	49	0%	4	23%R
40	16	69%R	7.2	0%	287	44%I	49	0%	4	23%R
80	7	87%R	7.2	0%	287	44%I	49.5	1%I	6	15%I
160	5	90%R	7.2	0%	295	48%I	50.2	2.4%I	26	>100%I
320	10	81%R	6.91	4%R	297	49%I	50	2.5%I	30	>100%I
640	10	81%R	7.2	0%	297	49%I	53	8.4%I	43	>100%I

I: Increase, R: Reduction

Table 4.18: High Turbid Water Samples Treated by Carbonized Eggshells

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	16	84%R	6.9	5.5%R	344	11%I	47.7	3.6%R	4	30%R
40	13	87%R	7.1	3.4%R	344	11%I	49	1%R	5	12%R
80	12	88%R	7.1	3.4%R	344	11%I	49.3	0.4%R	6	5%I
160	14	86%R	7.1	3.4%R	344	11%I	49.7	0.4%I	6	5%I
320	15	85%R	7.2	1.4%R	344	11%I	51.2	3.4%I	6	5%I
640	16	84%R	7.2	1.4%R	346	12%I	52	5.1%I	6	5%I

I: Increase, R: Reduction

To further summarize, figure 4.14 illustrates turbidity removal obtained with raw and carbonized eggshells coagulants for low, medium and high turbid water samples.

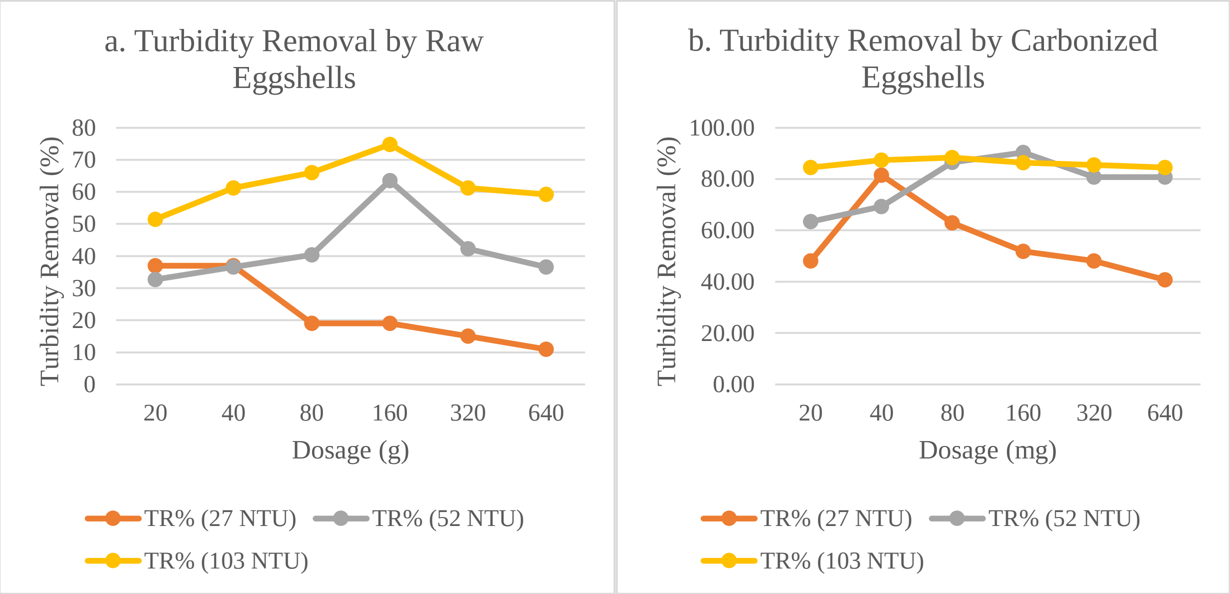


Figure 4.14: Percent Turbidity Removal at Various Eggshells Dosages.
(a) Turbidity Removal by Raw Eggshells (%). (b) Turbidity Removal by Carbonized Eggshells.
TR%: Turbidity Removal%.

The highest percent of turbidity removal at all coagulant dosages was achieved using carbonized eggshells coagulant for the high turbid water samples. It was also observed that the carbonization treatment significantly improved the performance of this coagulant. By interpreting the turbidity values shown in tables 4.13-4.18, acceptable turbidity levels that comply with the WHO Guidelines for Drinking Water (5 NTU) were achieved by carbonized eggshells at the low and moderate levels using coagulant doses of 40 mg and 160 mg. The changes induced on the overall water quality parameters at those doses complied with the WHO Guidelines for Drinking Water except for color, which exceeded the guideline after treatment with 160 mg coagulant dose for the medium turbid water sample. Thus, the optimum selected dose for turbidity removal was 40 mg at the low turbid water sample. Figures 4.15- 4.18 show the overall changes in the water quality as indicated by color, TDS, pH, and alkalinity at the different dose levels of the raw and carbonized eggshells coagulants.

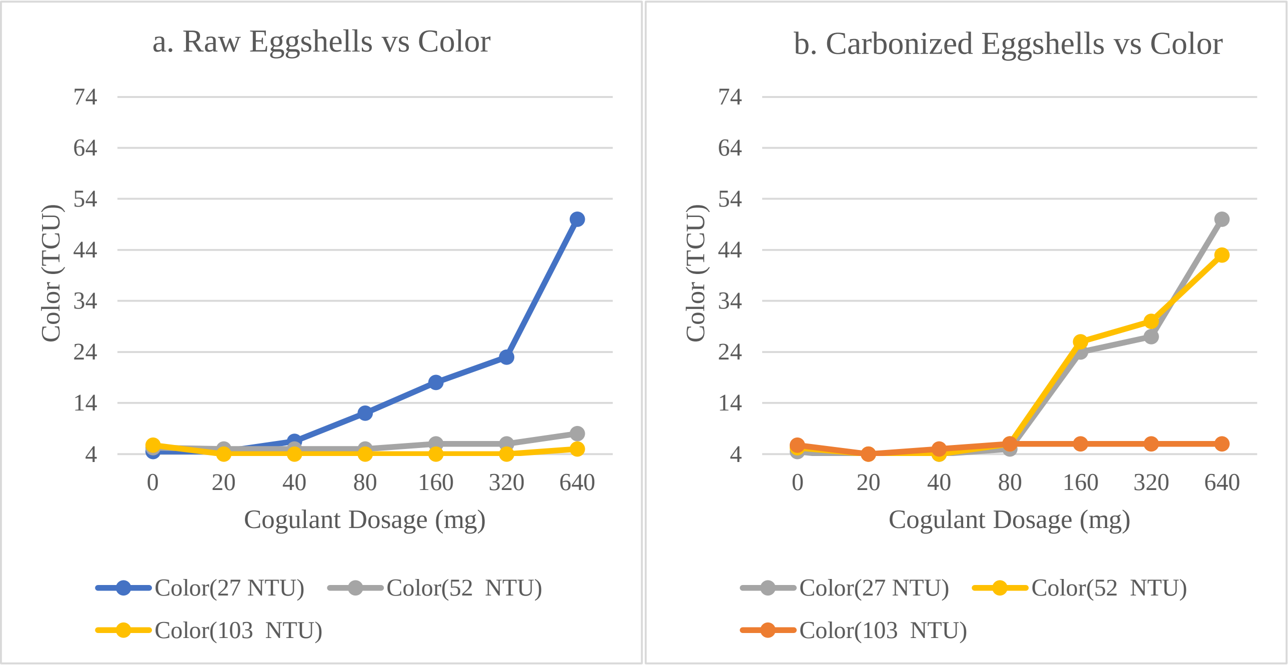


Figure 4.15: Effect of Eggshells Dosage on Color (TCU).
(a) Raw Eggshells vs Color. (b) Carbonized Eggshells vs Color.

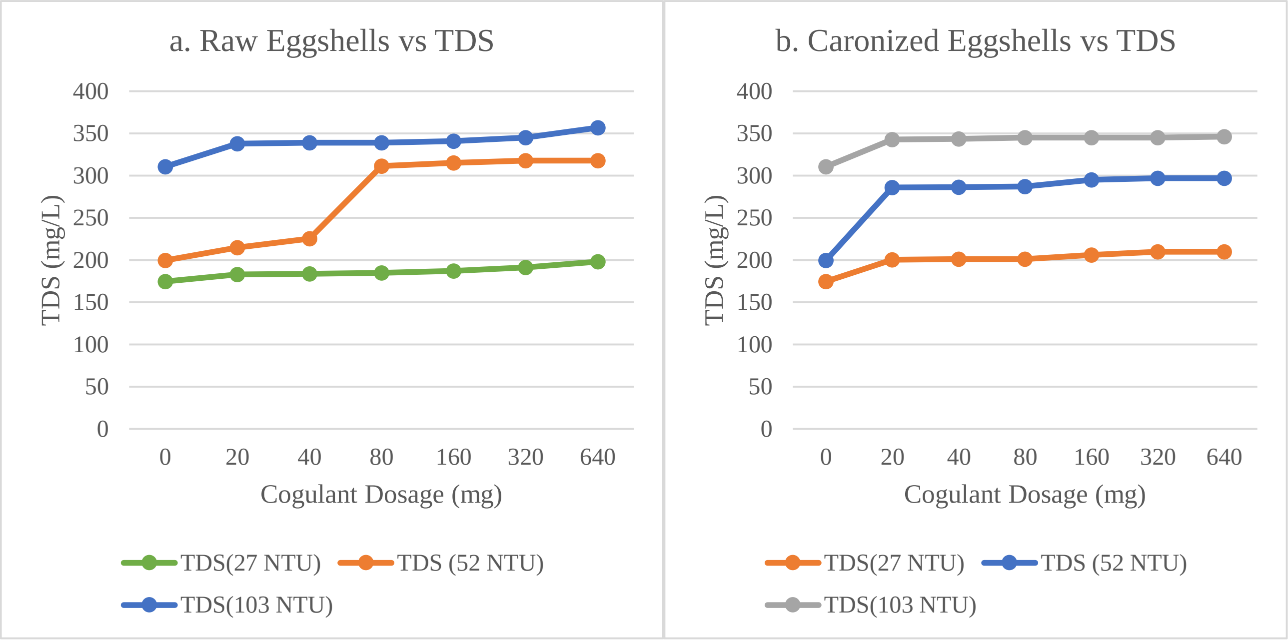


Figure 4.16: Effect of Eggshells Dosage on TDS (mg/L).
(a) Raw Eggshells vs TDS. (b) Carbonized Eggshells vs TDS. TDS, Total Dissolved Solids.

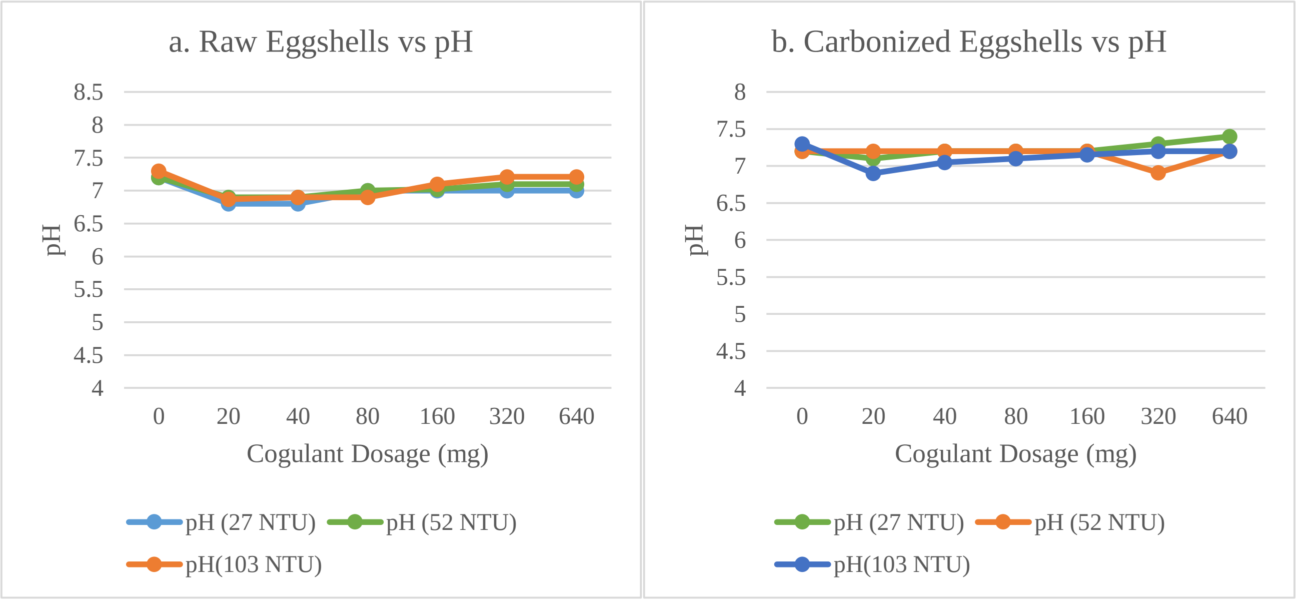


Figure 4.17: Effect of Eggshells Dosage on pH.
(a) Raw Eggshells vs pH. (b) Carbonized Eggshells vs pH.

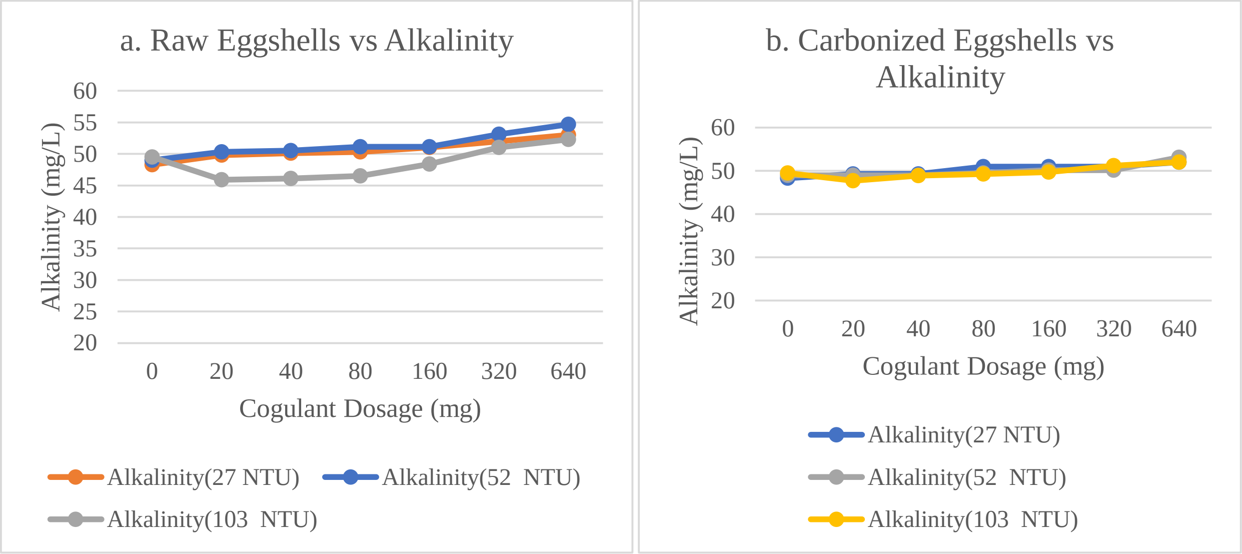


Figure 4.18: Effect of Eggshells Dosage on Alkalinity.
(a) Raw Eggshells vs Alkalinity. (b) Carbonized Eggshells vs Alkalinity.

It can be noted from the illustrated figures that at the selected dose for turbidity removal, minimum changes in the water quality parameters were observed. Figures 4.17b, 4.18b, 4.19b, and 4.20b show that the color, TDS, pH, and alkalinity values complied with the WHO Guidelines for Drinking Water at the selected dose (40 mg) of the carbonized eggshells. Accordingly, the chosen dose, which is 40 mg, was considered optimal for a low turbid water sample. Additionally, the ANOVA test using Minitab 19 software was employed to observe the influence of the eggshells dosage (raw and carbonized) on turbidity removal at a 90% confidence level as follow:

Table 4.19: ANOVA. Analysis of Variance for Eggshells Coagulant

a. ANOVA: TR% Versus Raw Eggshells Dose (g)						**a. ANOVA: TR% Versus Carbonized Eggshells Dose (g)**					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Source**	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Dose (g)	5	458.7	91.74	0.19	0.962	Dose (g)	5	549.6	109.9	0.32	0.894
Error	12	5857.3	488.11			Error	12	4180.6	348.4		
Total	17	6316.0				Total	17	4730.2			

ANOVA, Analysis of Variance. TR%, Turbidity Removal. DF, Total Degrees of Freedom. Adj SS, Adjusted Sums of Squares. Adj M, Adjusted Mean Squares. F-Value, Variation between Sample Means / Variation within the Samples. P-Value, Probability Value.

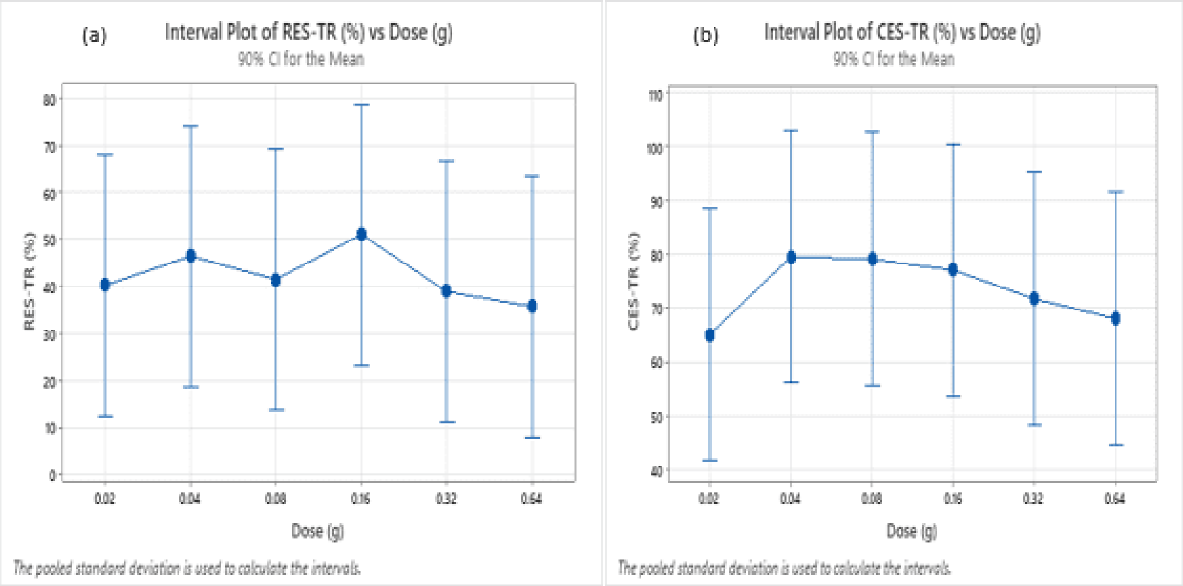


Figure 4.21: Interval Plot of Eggshells Dose versus TR% at 90% CI.
(a). Interval Plot of Raw Eggshells. (b) Interval Plot of Carbonized Eggshells. CI, Confidence Interval. TR%, Turbidity Removal.

Similar to the banana peels coagulants, the ANOVA test (Table 4.19) shows that increasing the eggshells coagulant dose did not match achieving higher turbidity removal. Accordingly, the interval plots (Figure 4.19) showed a non-linear correlation between the raw and carbonized eggshells coagulant dosage and the turbidity removal. Thus, it can be deduced that achieving the desirable turbidity removal by the eggshells coagulant depends on selecting an optimum dose. Also, the studies presented in chapter 2 show that similar to any coagulant, the optimum dose of the eggshells coagulant depends on the coagulation process conditions such as contact time, mixing speed, pH and temperature, and the physical-chemical characteristics of the polluted water samples (Bartby, 2016; Haghiri et al., 2018).

4.3.2. Destruction of Pathogenic Microorganisms

Destruction of E. coli pathogenic microorganisms was also studied on E. coli bacteria using the eggshells treated extracts as presented earlier in chapter 3. Figure 4.20 shows the microscopy images of the E. coli strains ATCC® 25922 colonies grown on nutrient agar plates with membrane filters, treated with raw eggshells extract. Figure 4.21 shows the microscopy images of the E. coli strains ATCC® 25922 colonies grown on nutrient agar plates with membrane filters, treated by the carbonized eggshells extract. Moreover, table 4.20 shows the E. coli reduction rate obtained for raw and carbonized eggshells extracts.

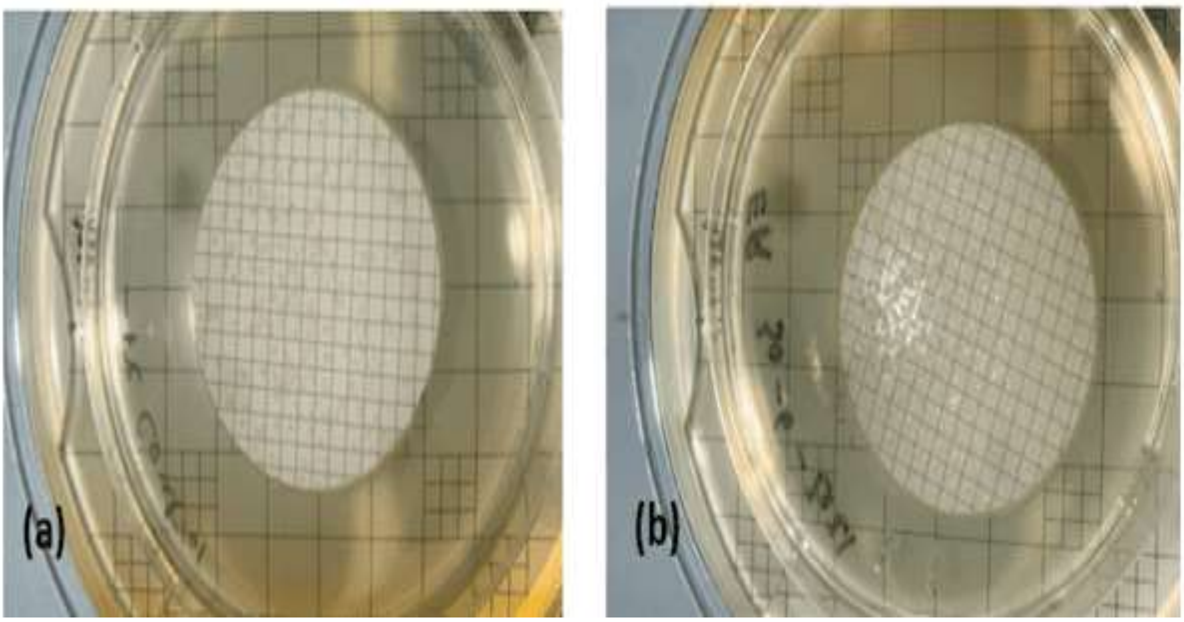


Figure 4.20: Reduction of E. coli in (a) Control Plate (b) Plate Treated with Raw Eggshells Extract (20 mg/ml)

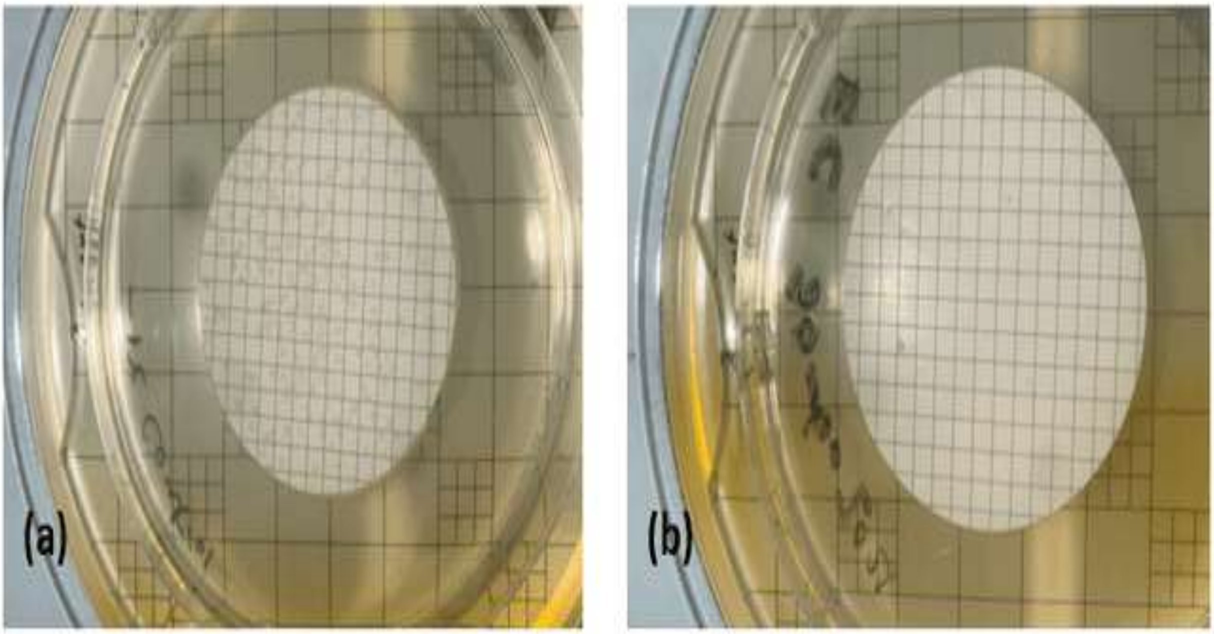


Figure 4.21: Reduction of E. coli in (a) Control Plate (b) Plate Treated with Carbonized Eggshells Extract (20 mg/ml)

Table 4.20: Percent Reduction of E. coli by Eggshells Extract.

Sample ID	Dose Concentration (mg/ ml)	nC (colonies/10 ml)	nM (colonies/10 ml)	E. coli Reduction%
ER	20	205	> 205 BO	-
EC	20	205	2	99%

ER: Eggshells Raw, EC: Eggshells Carbonized, nC: Number of colonies on the control plates with untreated membranes, nM: Number of colonies on the plates treated with treated membranes, BO: Bacteria Overgrowth. -: no reduction observed.

Figure 4.22b shows that the raw eggshells led to a tremendous increase in E. coli colonies compared to the negative control shown in figure 4.22a. Thus, table 4.20 shows over bacterial growth (OB) for raw eggshells. Earlier studies reported that organic agricultural wastes such as eggshells, if they were not thermally treated, could enhance the growth of pathogenic microorganisms due to the organic components that support the bacterial growth (Bouteleux et al., 2005). Thus, if this eco-coagulant/adsorbent is to be used for contaminants removal, integrating an additional water disinfection method is necessary to ensure microbiological water safety. On the other hand, experimenting with the carbonized extract showed that 20 mg/ml dose significantly reduced the E. coli bacteria. The E. coli reduction rate was around 99%, as shown in table 4.20. This is in line with the studies presented in chapter 2, reporting that combusting eggshells will result in converting the calcium carbonate (CaCO3), which is the main component of the eggshells, into calcium oxide (CaO), which is an antimicrobial agent (Ohshima et al., 2015). Thus, it can be concluded from these preliminary results that carbonized eggshells can have the potential to be an environmentally friendly antibacterial agent in the water treatment field. Although, further studies are needed with more data and modeling designs to confirm the antibacterial properties of carbonized eggshells since the WHO Guidelines for Drinking Water requires the eradication of pathogenic microorganisms for drinking water purposes (WHO, 2017).

4.3.3. Heavy Metals Removal

Similar to the banana peels adsorbents, removal of chromium and lead ions by eggshells were also experimented to identify the optimum conditions (the adsorbent dose and contact time) to achieve the best reduction levels results with minimal resources. The removal rates of chromium and lead and the adsorption capacity of eggshell's adsorbents were calculated using the Removal Rate (R %) and Adsorption Capacity (q_e) equations presented in chapter 3. The calculated data were interpreted by the ANOVA, Pareto charts, and normal probability plots using the response surface regression analysis at 95% confidence level by Minitab 19 software.

Table 4.21 illustrates the ANOVA computed for the chromium and lead removal by the eggshell adsorbents. And, figures 4.24 - figure 4.25 represents the Pareto charts and Normal Probability plots for the eggshells adsorbents. Accordingly, it can be concluded that the adsorbent dose and contact time are statistically significant for chromium and lead removal by raw and carbonized eggshells. In contrast, the chromium and lead concentrations are not statistically significant since P-value>0.05. Additionally, the Pareto charts in figures 4.22a and 4.22c show that the adsorbent dose exhibited the most considerable influence on the chromium removal rates by the raw and carbonized eggshells, followed by the contact time. On the other hand, figures 4.24b and 4.24d show that the contact time exhibited the most considerable influence on the lead removal rates by the raw and carbonized eggshells, followed by the adsorbent dose. As such, the normality evidence has been satisfied for the raw and carbonized eggshells adsorbents since P-value> 0.05 as (Figure 4.23a 4.23d).

Table 4.21: ANOVA for Lead and Chromium Removal by Eggshells.
(a) ANOVA for R% (CR)_RES. (b) ANOVA for R% (Pb)_RES. (c) ANOVA for R% (CR)_BES. (d) ANOVA for R% (Pb)_BES.

(a) ANOVA for R%(CR)_ RES						**(b) ANOVA for R%(Pb)_ RES**					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Source**	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	9	10.0385	1.11538	165.83	0.000	**Model**	9	51.5849	5.7317	105.42	0.000
Linear	3	2.7728	0.92426	137.41	0.000	**Linear**	3	14.5501	4.8500	89.21	0.000
AD	1	1.7887	1.78867	265.92	0.000	**AD**	1	3.5639	3.5639	65.55	0.000
HMC	1	0.0001	0.00010	0.01	0.907	**HMC**	1	0.0511	0.0511	0.94	0.370
CT	1	0.9840	0.98400	146.29	0.000	**CT**	1	10.9351	10.9351	201.13	0.000
Square	3	2.9876	0.99588	148.06	0.000	**Square**	3	17.0189	5.6730	104.34	0.000
Error	6	0.0404	0.00673			**Error**	6	0.3262	0.0544		
Lack-of-Fit	3	0.0302	0.01006	2.97	0.198	**Lack-of-Fit**	3	0.2810	0.0937	6.22	0.084
Pure Error	3	0.0102	0.00339			**Pure Error**	3	0.0452	0.0151		
(c) ANOVA for R%(CR)_ BES						**(d) ANOVA for R%(Pb)_ BES**					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Source**	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	9	0.338937	0.037660	141.43	0.000	**Model**	9	43.2255	4.8028	56.99	0.000
Linear	3	0.088722	0.029574	111.06	0.000	**Linear**	3	10.3716	3.4572	41.02	0.000
AD	1	0.059157	0.059157	222.16	0.000	**AD**	1	2.4181	2.4181	28.69	0.002
HMC	1	0.000001	0.000001	0.00	0.964	**HMC**	1	0.0553	0.0553	0.66	0.449
CT	1	0.029564	0.029564	111.03	0.000	**CT**	1	7.8981	7.8981	93.72	0.000
Square	3	0.110878	0.036959	138.80	0.000	**Square**	3	15.2154	5.0718	60.18	0.000
Error	6	0.001598	0.000266			**Error**	6	0.5057	0.0843		
Lack-of-Fit	3	0.000880	0.000293	1.23	0.436	**Lack-of-Fit**	3	0.4434	0.1478	7.13	0.070
Pure Error	3	0.000718	0.000239			**Pure Error**	3	0.0622	0.0207		

ANOVA, Analysis of Variance. TR%, Turbidity Removal. DF, Total Degrees of Freedom. Adj SS, Adjusted Sums of Squares. Adj M, Adjusted Mean Squares. F-Value, Variation between Sample Means / Variation within the Samples. P-Value, Probability Value. AD, Adsorbent Dose, HMC, Chromium and Lead Concentration. CT, Contact Time.

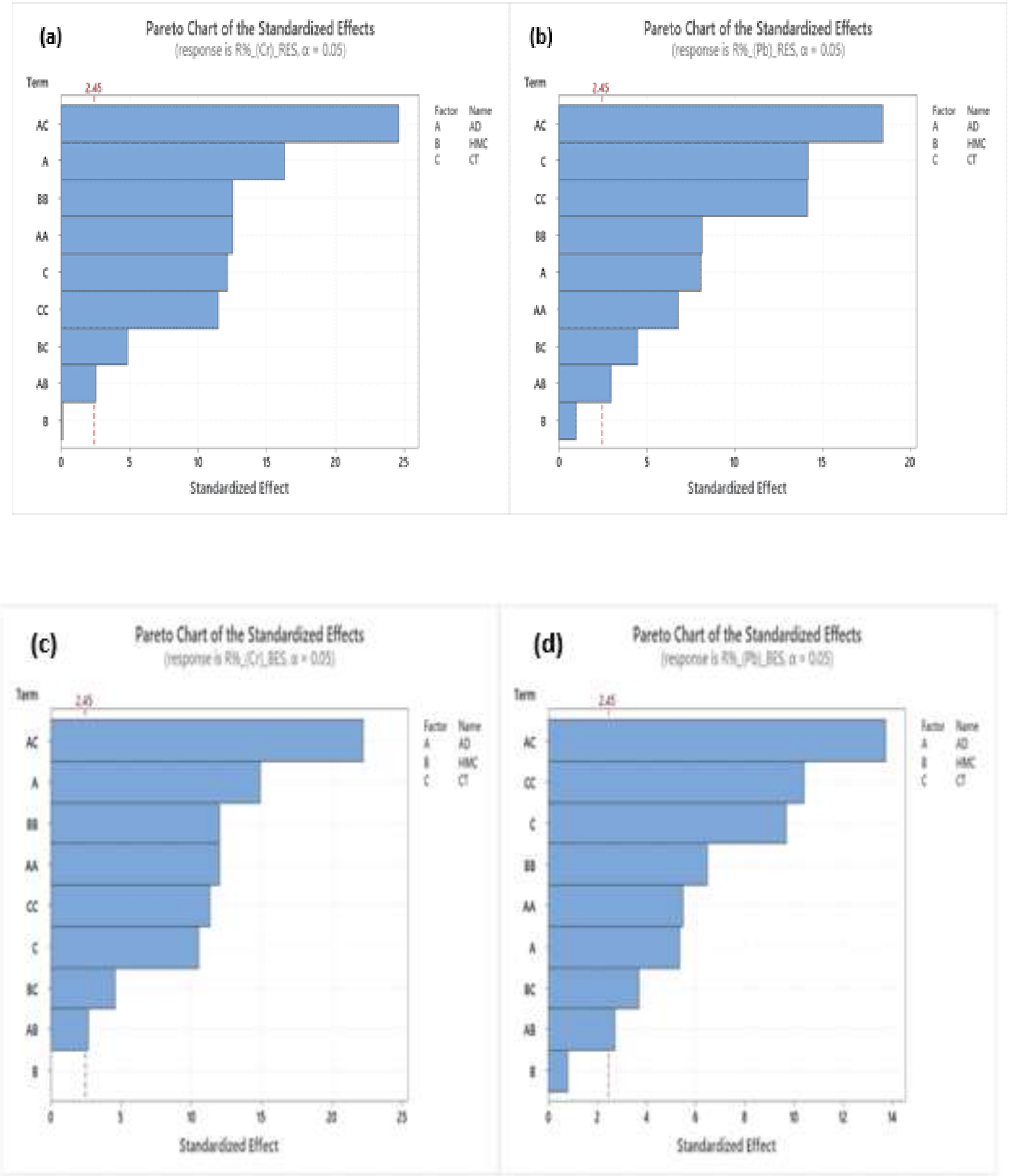


Figure 4.22: Eggshells Pareto Charts.
(a) Pareto Chart for R % (Cr) _RES. (b) Pareto Chart for R % (Pb)_RES. (c) Pareto Chart for R % (Cr) _BES. (d) Pareto Chart for R % (Pb)_BES.R % (Cr) _RES: Chromium Removal Rate for Raw Eggshells. R % (Pb)_RES: Lead Removal Rate for Eggshells. R % (Cr) _BES: Chromium Removal Rate for Burnt Eggshells. R % (Pb)_BES: Lead Removal Rate for Burnt Eggshells. AD: Adsorbent Dose, mg. HMC: Chromium and Lead Concentration, mg/L. CT: Contact Time, minutes.

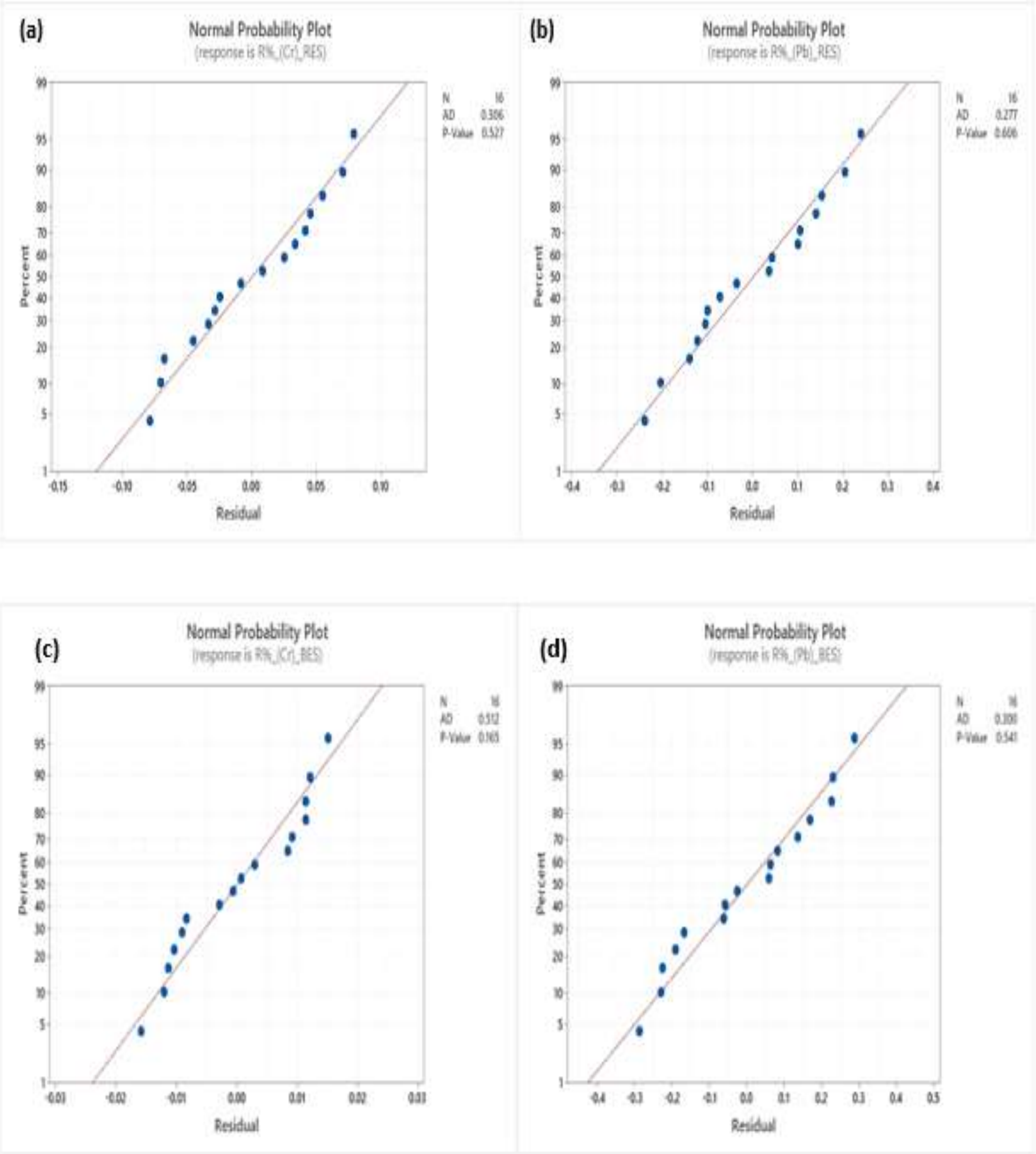


Figure 4.23: Eggshells Normal Probability Plots.
(a) Normal Probability Plot for R% (Cr) _RES. (b) Normal Probability Plot for R% (Pb) _RES. (c) Normal Probability Plot for R% (Cr)_BES. (d) Normal Probability Plot for R% (Pb) _BES. R % (Cr) _RES: Chromium Removal Rate Eggshells. R % (Pb) _RBP: Lead Removal Rate for Raw Eggshells. R % (Cr) _BES: Chromium Removal Rate for Burnt Eggshells. R % (Pb) _BES: Lead Removal Rate for Burnt Eggshells. AD: Anderson-Darling.

As such, it is concluded from the statistical analysis of this preliminary pilot study on eggshells adsorbents that achieving high removal rates of chromium and lead is greatly influenced by the proper selection of the adsorbent dose and treatment time. This is in line with Tizo et al. study, in 2018 that showed that the efficiency of trace metals removal by eggshells adsorbents depends on the combination of various factors such as the adsorbent dose, contact time, initial concentration of the contaminants, and the physio-chemical properties of the water sample to be treated (Tizo et al., 2018). Thus, optimum chromium and lead removal depend on the combination of those factors. Accordingly, to determine the better conditions for the chromium and lead removal, contour plots (Figures 4.24-4.25) were used to define high chromium and lead removal outcomes at the lowest possible doses, as follow:

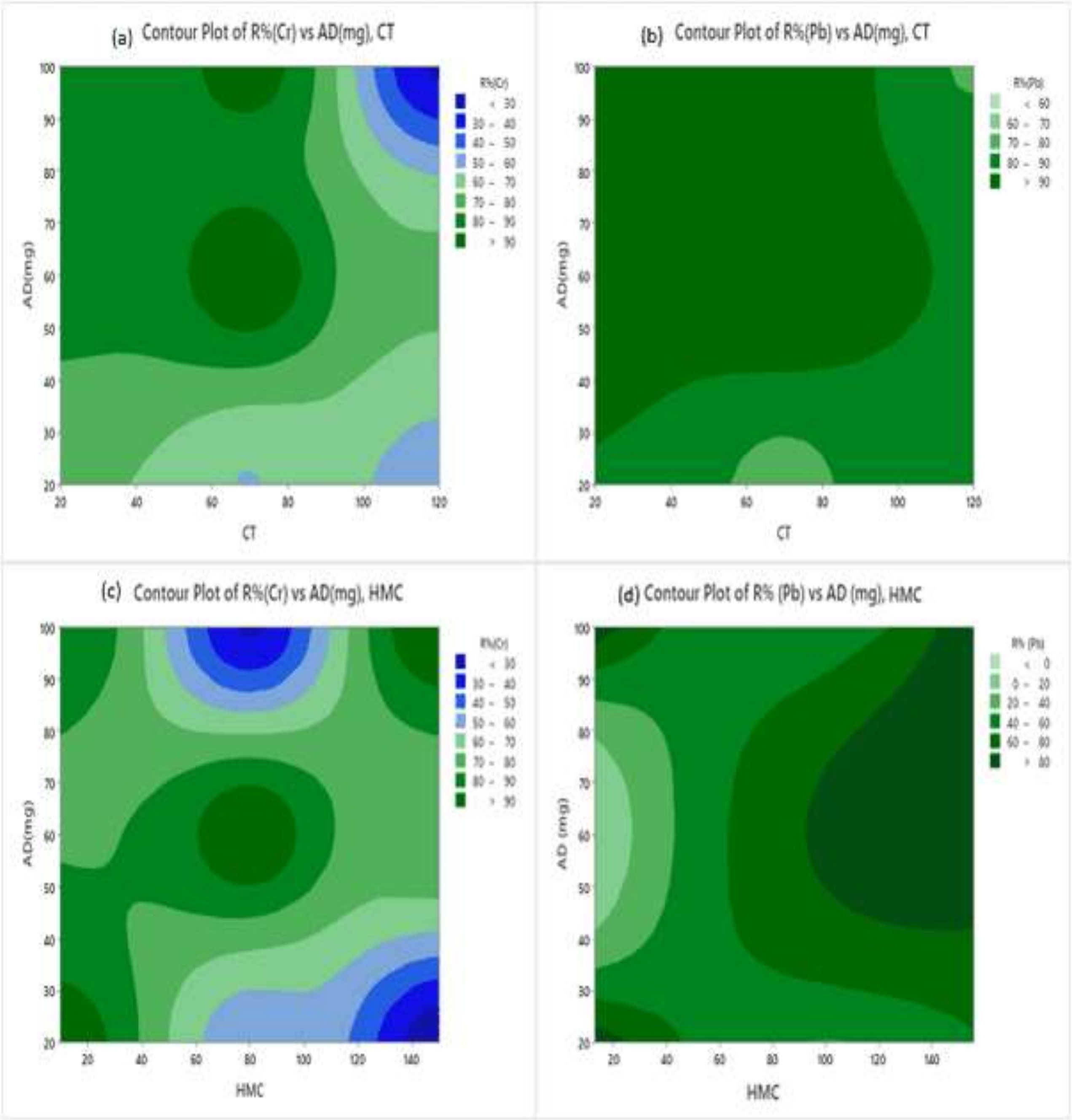


Figure 4.24: Contour Plots of Raw Eggshells.

(a) Contour Plot of R %(Cr) vs. AD, CT. (b) Contour Plot of R %(Pb) vs AD, CT. (c) Contour Plot of R%(Cr) vs. AD, HMC. (d) Contour Plot of R %(Pb) vs. AD, HMC. R% (Cr): Chromium Removal Rate. R %(Pb): Lead Removal Rate. AD: Adsorbent Dose, mg. HMC: Chromium and Lead concentration, ppm

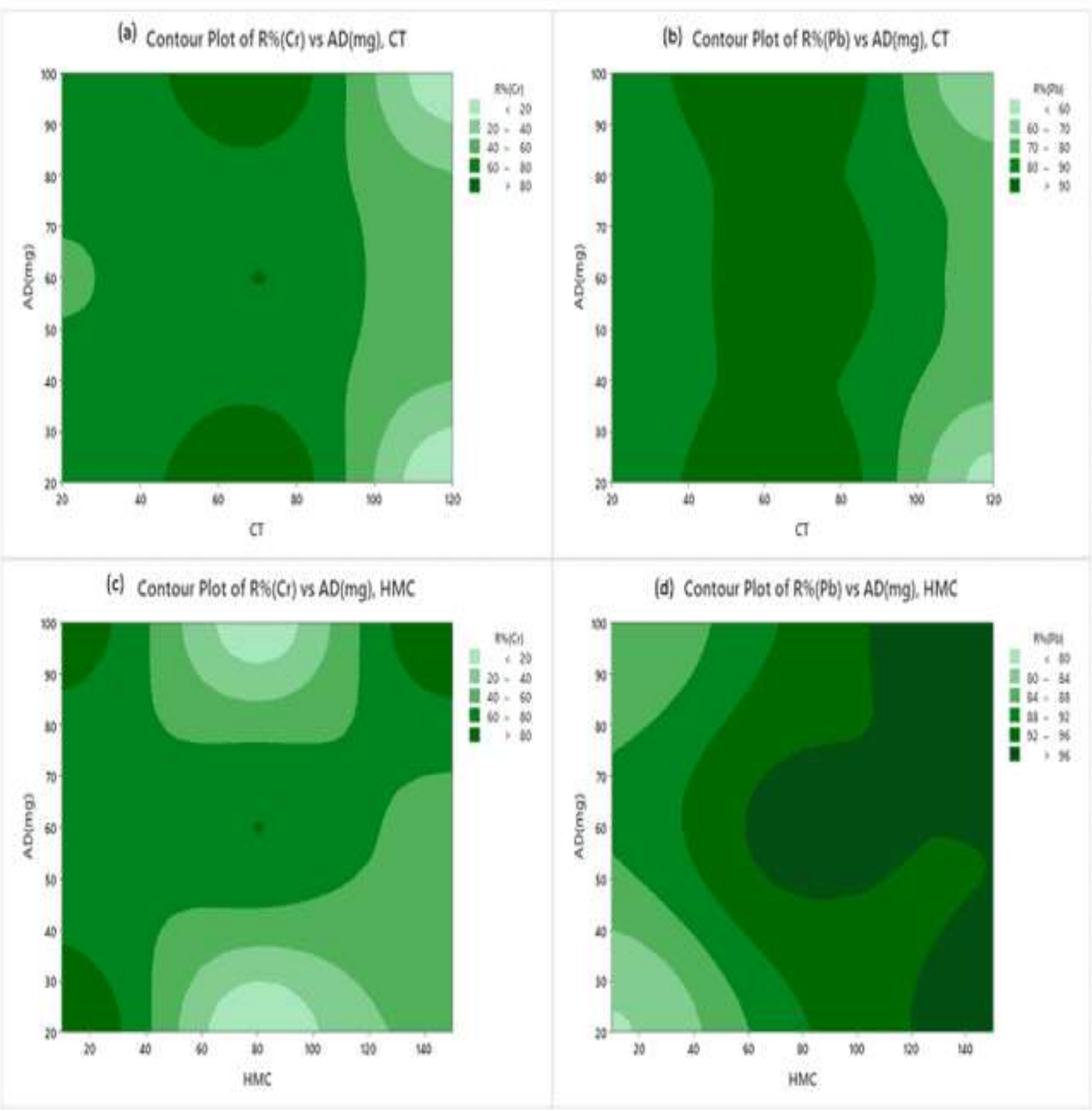


Figure 4.27: Contour Plots of Carbonized Eggshells.
(a) Contour Plot of R %(Cr) vs. AD, CT. (b) Contour Plot of R %(Pb) vs AD, CT. (c) Contour Plot of R%(Cr) vs. AD, HMC. (d) Contour Plot of R %(Pb) vs. AD, HMC. R% (Cr): Chromium Removal Rate. R %(Pb): Lead Removal Rate. AD: Adsorbent Dose, mg. HMC: Chromium and Lead

By interpreting figure 4.26, the least selected dose for achieving high chromium and lead removal rates by the raw eggshells can be 60 mg and 20 mg. On the other hand, figure 4.27 shows that high chromium and lead removal rates can be achieved at 20 mg by the carbonized eggshells. Still, the contour plots show that the efficient chromium and lead removal rates achieved at the lowest possible adsorbent dose depend on the associated contact time and heavy metals concentration. On the other hand, to comply with the WHO Guidelines for Drinking Water for chromium and lead, at least a 99.75% chromium removal rate and a 99.95% lead removal rate must be achieved. Thus, the values selected from the contour plots cannot be taken for granted, as discussed earlier in the banana peels section. However, the contour plots were useful to observe the overall performance of the eggshells adsorbents at different conditions, which can be optimized in follow-up studies.

As such, , for this preliminary pilot study, the optimum conditions for chromium and lead removal by the raw and carbonized eggshells were computed by the Minitab 19 Response Optimizer of the factorial DOE. Accordingly, tables 4.22 and 4.23 show the optimum treatment conditions obtained from figures 4.28 and 4.29, which achieved the highest chromium and lead removal rates by the eggshells adsorbents complying with the WHO Guidelines for Drinking Water as follow:

Table 4.22: Optimum Conditions for Chromium and Lead Removal by the Raw Eggshells Adsorbent.

Optimum Conditions for Chromium and Lead Removal by Raw Eggshells			
Chromium Removal, R(Cr)%		Lead Removal, R(Pb)%	
Optimum adsorbent dose, mg	60	Optimum adsorbent dose, mg	60
Optimum contact time, min	78	Optimum contact time, min	120
Optimum initial chromium concentration, mg/L	12	Optimum initial lead concentration, mg/L	14
R(Cr%)	99.75%	R(Pb%)	99.95%

Table 4.22: Optimum Conditions for Chromium and Lead Removal by Carbonized Eggshells Adsorbent.

Optimum Conditions for Chromium and Lead Removal by Carbonized Eggshells			
Chromium Removal, R(Cr)%		Lead Removal, R(Pb)%	
Optimum adsorbent dose, mg	94	Optimum adsorbent dose, mg	60
Optimum contact time, min	76	Optimum contact time, min	120
Optimum initial chromium concentration, mg/L	150	Optimum initial lead concentration, mg/L	18
R(Cr%)	99.75%	R(Pb%)	99.95%

It can be deduced from tables 4.22 and 4.23that the raw eggshells adsorbent achieved desirable chromium and removal rates at a lower dose than the carbonized form. Still, the carbonized eggshells obtained the desired chromium reduction value for solutions with higher chromium concentrations (Table 4.23). Thus, the preliminary work shows that enhancing the eggshells adsorbent with carbonization treatment would be more effective for situations that require treating highly contaminated water with chromium. Additionally, the optimum treatment time for the chromium and lead removal by the eggshells adsorbent was high. The optimum contact time exceeded the 1-hour duration, which is in line with similar reported studies indicating that increasing the treatment time to the equilibrium limit can influence heavy metals removal such as fluoride, which was optimally removed after 120 minutes according to Bhaumik et al. study (Bhaumik et al., 2012). As such, a similar behavior could have been applied in this study for chromium and lead removal. However, a longer treatment time will constitute a constraint to water treatment purposes, especially under emergency conditions. Thus, additional work and further studies are needed to address this issue.

4.3.4. Efficiency of Eggshells for Contaminants Removal in Water Treatment

To reflect on overall efficiency of eggshell products in the removal of the specified water contaminants, table 4.24 presents all the experimental input variables: the eggshells dose, contact time, initial contaminant concentration (chromium, lead, turbidity, and E.coli), and the corresponding output variables (chromium removal rate, lead removal rate, turbidity removal, and E. coli reduction rate). Similar to the banana peels, the input variables were selected based on the lowest possible ranges that achieved treatment results in line with the WHO Guidelines for Drinking Water (WHO, 2017).

Table 4.24: Eggshells Overall Profile in Enhancing Water Quality and Safety

Chromium Removal				
Input Variables			**Output Variables**	
Adsorbent dose (mg)	**Contact time (min)**	**Chromium Level (mg/L)**	**R (Cr%)**	**Cre, mg/L**
A. Raw Eggshells				
60	78	12	99.75%	0.05
Compliance with WHO Guidelines for Drinking Water for Chromium (0.05 mg/L)			Comply	
B. Carbonized Egshells				
94	76	150	99.75%	0.05

Compliance with WHO Guidelines for Drinking Water for chromium (0.05 mg/L)				Comply	
Lead Removal					
Input Variables				**Output Variables**	
Adsorbent dose (mg)	**Contact time (min)**		**Lead Level (mg/L)**	**R (Pb%)**	**Pbe, mg/L**
A. Raw Eggshells					
60	120		14	99.95%	0.01
Compliance with WHO Guidelines for Drinking Water for lead (0.01 mg/L)				Comply	
B. Carbonized Eggshells					
60	120		18	99.95%	0.01
Compliance with WHO Guidelines for Drinking Water for lead (0.01 mg/L)				Comply	
Turbidity Removal					
Input Variables				**Output Variables**	
Adsorbent dose (mg)	**Contact time (min)**		**Initial Turbidity (NTU)**	**TR (%) Turbidity removal rate**	**Final Turbidity (NTU)**
	Mixing time	**Settling time**			
Carbonized Eggshells					
40	20	20	27	81%	5
Compliance with WHO Guidelines for Drinking Water for turbidity (5 NTU)				Comply	
Overall Induced Changes in the Water Quality					
Color (TCU): 5				Comply	
Total Dissolved Solids (mg/L): 312				Comply	
pH: 7.1				Comply	
Alkalinity (mg/L): 49.5				Comply	
E. coli Reduction					
Input Variables				**Output Variables**	
Adsorbent dose (mg)	**Contact time (min)**	**Initial E. coli count (colonies/ 10 ml)**	**E. coli Reduction%**	**Final E. coli count (colonies/ 10 ml)**	
Carbonized Eggshells					
200	30	205	99%	2	
Compliance with WHO Guidelines for Drinking Water (0)				Does not comply	

R (Cr %), Chromium Removal Rate %. R (Pb %), Lead Removal Rate %.
TR%, Turbidity Removal Rate %. NTU, Nephelometric Turbidity Unit. TCU, True Color Units.

To conclude, table 4.24 shows that the eggshells eco-adsorbent/coagulant selected doses could achieve desirable chromium, lead, and turbidity removal in compliance with the WHO Guidelines for Drinking Water. Both raw and carbonized eggshells exhibited desirable chromium and lead reduction under the selected experimental conditions, as shown in table 4.24. Moreover, these preliminary pilot results show that using the carbonized eggshells for highly contaminated Water with chromium would be more favorable. Accordingly, it can be concluded that the optimum conditions for chromium and lead removal by the eggshells adsorbent exhibited a similar profile to that of banana peels adsorbents. Still, for drinking water treatment purposes, the optimum chromium and lead removal by the eggshells adsorbents will vary depending on the treatment conditions and other factors such as the type and concentration of the contaminant to be removed and the water physical-chemical characteristics as previously noted in an earlier study (Bhaumik et al., 2012). Additionally, eggshells products show more promise for turbidity removal after carbonization. Also, the preliminary pilot results showed that the carbonized eggshells adsorbent was very effective in reducing E. coli bacteria by 99%. Thus, additional studies are needed to confirm and optimize the disinfecting capacity of the eggshells adsorbent. Also, follow-up studies to optimize the overall performance of eggshells eco-adsorbents/coagulants in water treatment would need more data and modeling designs.

4.4. Water Treatment by Ovalbumin Protein

The ovalbumin protein from egg whites, a potential animal-based ecofriendly adsorbent/coagulant, was used to determine the removal of turbidity and reduction of pathogenic microorganisms from contaminated water sources. Like the banana peels and eggshells' eco-adsorbents/coagulants, the main objective was to determine the optimal dose to reduce those specific types of contaminants without affecting the overall water quality and safety.

4.4.1. Turbidity Removal

The efficiency of the ovalbumin protein in reducing water turbidity was investigated using low, medium, and high turbid water samples. Tables (4.25-4.27) show the characteristics of the turbid water samples treated with the ovalbumin protein coagulant.

Table 4.25: Low Turbid Water Samples Treated by Ovalbumin

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	15	44%	7.1	2.1%R	180	3%I	46.4	4%R	4	11%R
40	14	48 %R	7.1	2.1%R	183	5%I	47.2	2.3%R	5	11%I
80	7	74%R	7.2	0%	191	10%I	48	0.6%R	6	33%I
160	4	85%R	7.2	0%	210	20%I	50	3.5%I	13	>100%I
320	6	78%R	7.3	1.4%I	211	21%I	51	5.6%I	21	>100%I
640	8	70%R	7.3	1.4%I	211	21%I	51	5.6%I	31	>100%I

I: Increase, R: Reduction

Table 4.26: Moderate Turbid Water Samples Treated by Ovalbumin

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	23	56%R	7	3.5%R	200	0.25%I	47.3	3.5%R	5	4%R
40	17	67%R	7.05	2.1%R	209	4.8%I	48	2%R	5	4%R
80	13	75%R	7.1	1.4%R	215	8%I	48.7	0.6%R	6	33%I
160	8	85%R	7.1	1.4%R	233	17%I	50.1	2.2%I	8	>100%I
320	4	92%R	7.2	0%	233	17%I	50.1	2.2%I	13	>100%I
640	8	85%R	7.2	0%	235	18%I	51.3	4.7%I	16	>100%I

I: Increase, R: Reduction

Table 4.27: High Turbid Water Samples Treated by Ovalbumin

Dose (mg)	Turbidity		pH		TDS		Alkalinity		Color	
	Level (NTU)	Change | (%) |	Level	Change | (%) |	Level (mg/L)	Change | (%) |	Level (mg/L)	Change | (%) |	Level (TCU)	Change | (%) |
20	21	80%R	7.1	2.7%R	338	1.5%I	49	1%R	4	30%R
40	17	84%R	7.1	2.7%R	339	1.5%I	49.3	0.4%R	5	12%R
80	14	86%R	7.1	2.7%R	339	7%I	49.2	0.6%R	5	12%R
160	10	90%R	7.1	2.7%R	341	7.5%I	49.5	0%	6	5%I
320	5	95%R	7.2	1.5%R	345	8.4%I	50.3	1.6%I	6	5%I
640	8	92%R	7.2	1.5%R	357	9.2%I	50.5	2%I	7	23%I

I: Increase, R: Reduction

To further summarize, figure 4.26 illustrates turbidity removal by ovalbumin coagulants in low, medium and high turbid water samples.

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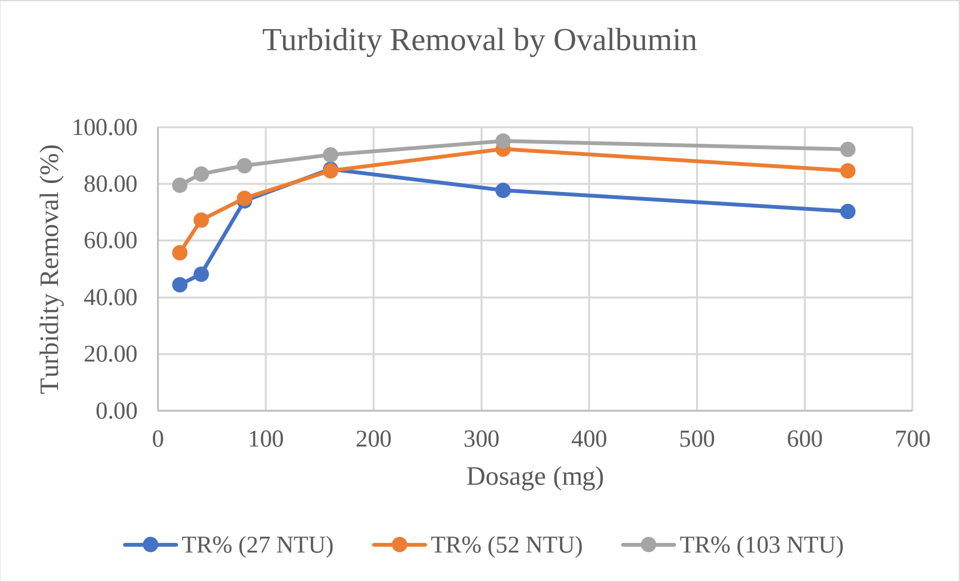


Figure 4.26: Percent Turbidity Removal at Various Ovalbumin Dosages. TR%: Turbidity Removal%.

The highest turbidity removal percentages were noted at all coagulant dosages in the high turbid water sample. By interpreting the turbidity levels shown in tables 4.25-4.27, acceptable turbidity levels that comply with the WHO Guidelines for Drinking Water (5 NTU), with overall changes in water quality were achieved at 160 mg for the low turbid water and 320 mg for the moderate and high turbid water samples. Figures 4.27- 4.30 show the overall changes in the water quality as indicated by color, TDS, pH, and alkalinity at different dose levels of this coagulant.

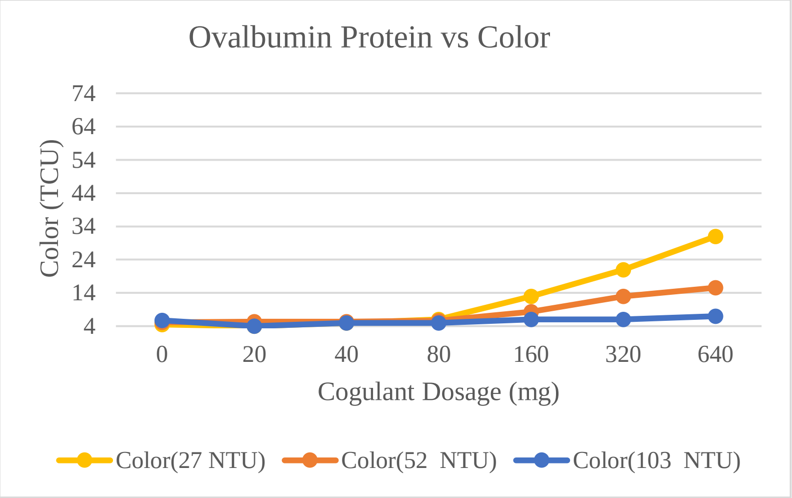


Figure 4.27: Effect of Ovalbumin Protein Dosage on Color (TCU).

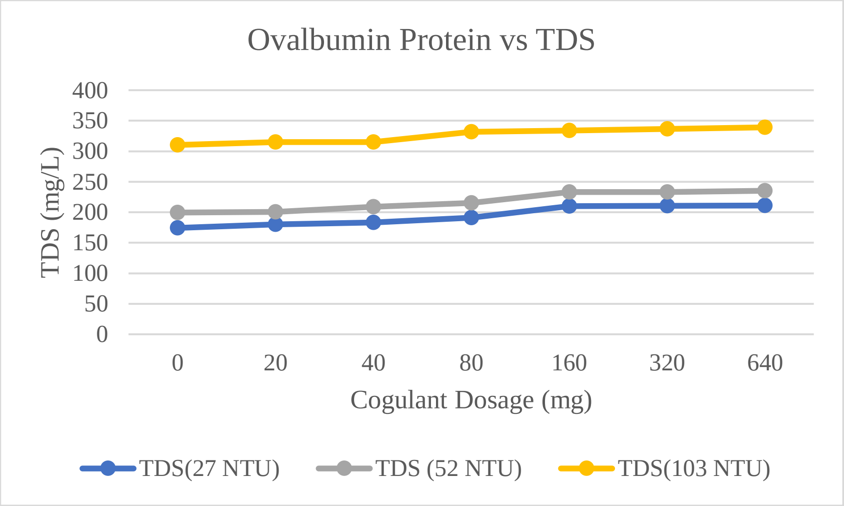


Figure 4.28: Effect of Ovalbumin Dosage on TDS (mg/L).
TDS, Total Dissolved Solids.

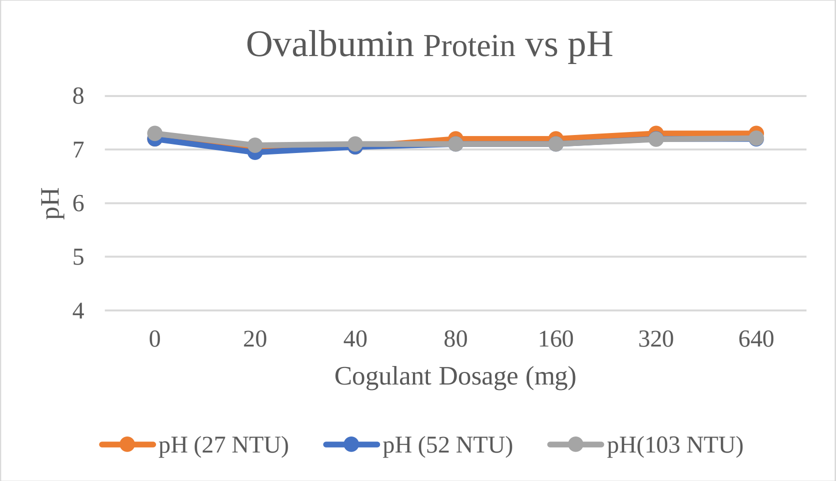


Figure 4.29: Effect of Ovalbumin Protein Dosage on pH.

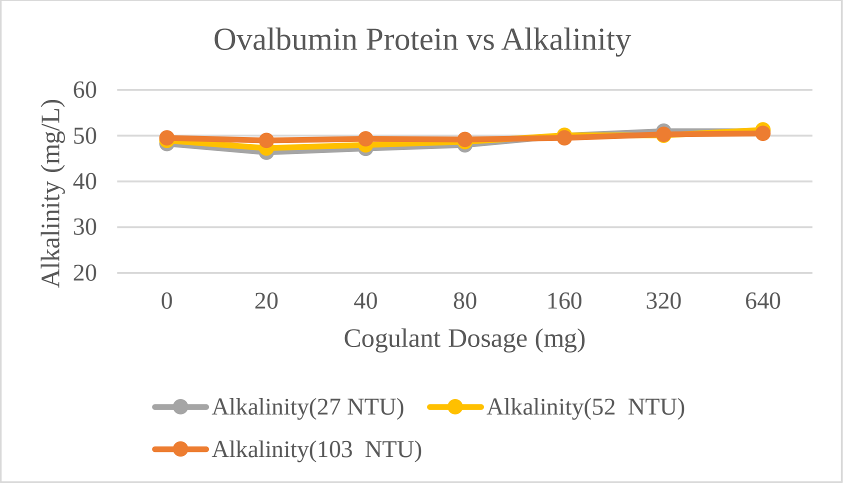


Figure 4.30: Effect of Ovalbumin Protein Dosage on Alkalinity (mg/L)

The selected coagulant doses for turbidity removal in low, medium, and high turbid water samples minimally affected the determined water quality parameters, as presented in Figures 4.31-4.34. And, the minimal induced changes were still in compliance with the WHO Guidelines for Drinking Water (WHO, 2017). Moreover, it was observed that the ovalbumin protein was the only eco-adsorbent/coagulant among the others tested in this preliminary pilot study that reduced turbidity levels to below recommended WHO Guidelines Drinking Water and for all low, medium, and high turbid water samples. The high turbidity removal levels by the egg-white albumin could be explained by its high molecular weight (45 kDa). The molecular weight of ovalbumin is probably a primary cause of the decisive aggregation action that was noticed during the jar test experiments, as in general, coagulation-flocculation processes could be facilitated by high molecular weight coagulants (Saritha et al., 2017).

Additionally, the ANOVA test using Minitab 19 software was employed to observe the influence of the ovalbumin protein dosage on turbidity removal at a 90% confidence level as follow:

Table 4.28: ANOVA. Analysis of Variance for Ovalbumin Protein Coagulant.

ANOVA: TR% Versus Ovalbumin Protein Dose (g)					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Dose (g)	5	1916	383.1	2.47	0.092
Error	12	1859	154.9		
Total	17	3774			

ANOVA, Analysis of Variance. TR%, Turbidity Removal. DF, Total Degrees of Freedom. Adj SS, Adjusted Sums of Squares. Adj M, Adjusted Mean Squares. F-Value, Variation between Sample Means / Variation within the Samples. P-Value, Probability Value.

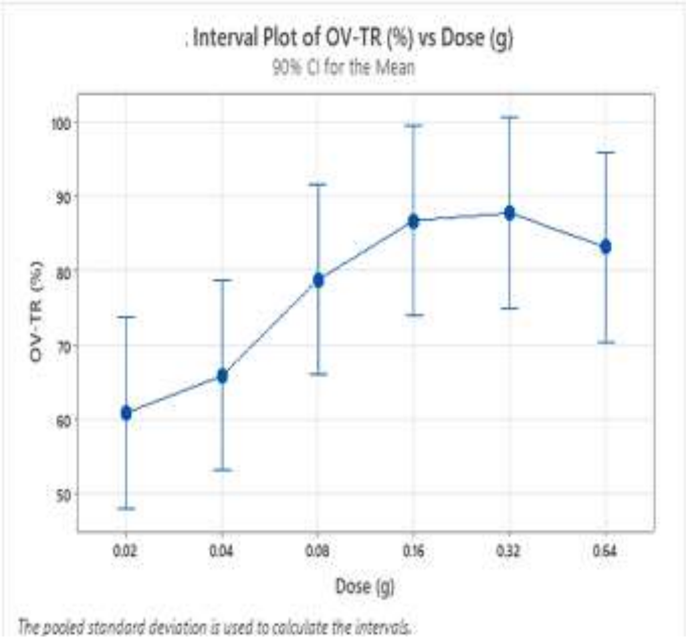


Figure 4.31: Interval Plot of Ovalbumin Protein Dose versus TR% at 90% CI.
CI, Confidence interval. TR%, Turbidity removal. Plot

The ANOVA test illustrated by table 4.28 shows that increasing the ovalbumin coagulant dose contributed to higher turbidity removal. Accordingly, the interval plot (figure 4.31) showed a linear correlation with coagulant dosing to a specific dosage limit of 320 mg, beyond which it started to decline. Thus, it can be deduced that increasing the ovalbumin coagulant dosage could enhance turbidity removal within a given range. However, similar to any other coagulant, the optimum dosage of ovalbumin protein is dependent on the coagulation process experimental settings in terms of contact time, mixing speed, pH, temperature, and the physical-chemical characteristics of the water samples.

4.4.2. Destruction of Pathogenic Microorganisms

Destruction of pathogenic microorganisms was also studied on E. coli bacteria using the ovalbumin extract, as presented earlier in chapter 3. Figure 4.32 shows the microscopy images of the E. coli strains ATCC® 25922 colonies grown on nutrient agar plates with membrane filters. Additionally, table 4.29 shows the E. coli reduction rate obtained by the ovalbumin protein extract.

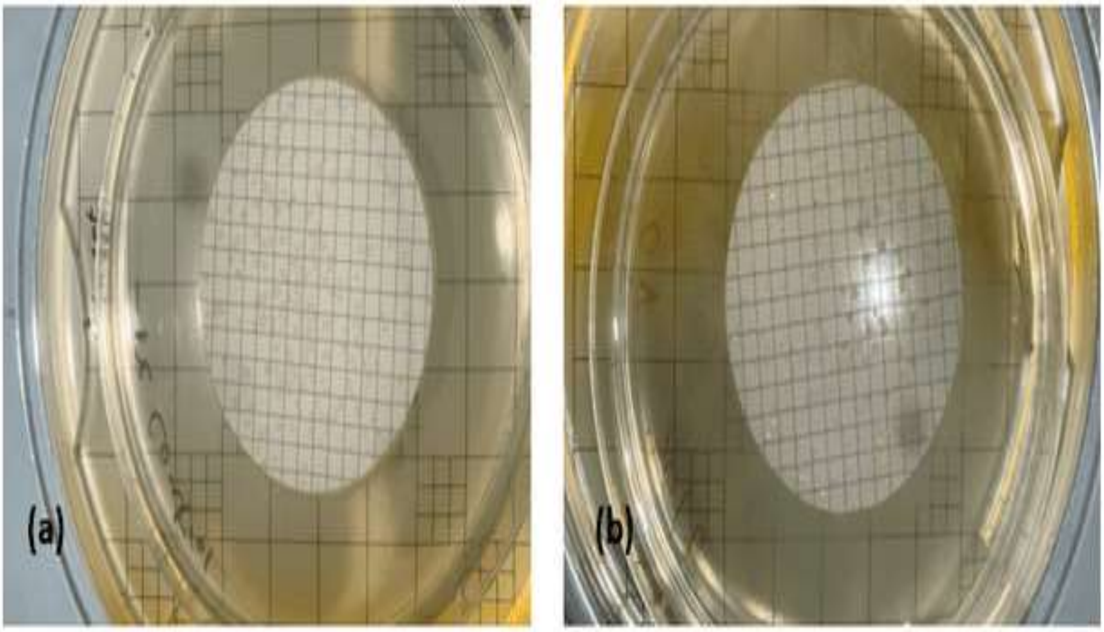


Figure 4.32: Reduction of E. coli in (a) Control Plate (b) Plate Treated with Ovalbumin Extract (20 mg/ml)

Table 4.29: Percent Reduction of E. coli by Ovalbumin Extract.

Sample ID	Dose Concentration (mg/ml)	nC (colonies/10 ml)	nM (colonies/10 ml)	E. Coli Reduction %
OV	20	205	113	45%

OV: Ovalbumin, nC: number of colonies on the control plates with untreated membranes, nM: number of colonies on the plates treated with treated membranes.

As such, ovalbumin protein reduced the E. coli colonies compared to the negative control plate (Figure 4.35a). Still, the percent reduction of E. coli achieved with 20 mg/ml ovalbumin extract was minimal (<50%) (Table 4.29). However, it can be concluded that the ovalbumin protein could have exhibited some disinfection properties. This may be because the egg-white represents a primary protection part for the egg from harmful microorganisms due to its alkaline pH and because it contains antibacterial proteins, as noted by previous studies (Guyot et al., 2013). However, further studies are needed for more data generation and modeling designs to explore this potential disinfection mechanism.

4.4.3. Efficiency of Ovalbumin for Contaminants Removal in Water Treatment

To reflect on the overall efficiency of the ovalbumin protein in the removal of turbidity and pathogenic microorganisms, table 4.30 shows the input variables: the ovalbumin coagulant dose, contact time, initial contaminant concentration (turbidity, and E.coli), and the corresponding output variables (turbidity removal, and E. coli reduction rate). The input variables were selected based on levels in compliance with the WHO Guidelines for Drinking Water (WHO, 2017).

Table 4.30: Ovalbumin Overall Profile in Enhancing Water Quality and Safety

<table>
<tr><td colspan="6">Turbidity Removal</td></tr>
<tr><td colspan="4">Input Variables</td><td colspan="2">Output Variables</td></tr>
<tr><td rowspan="2">Adsorbent dose (mg)</td><td colspan="2">Contact time (min)</td><td rowspan="2">Initial Turbidity (NTU)</td><td rowspan="2">TR (%) Turbidity removal rate</td><td rowspan="2">Final Turbidity (NTU)</td></tr>
<tr><td>Mixing time</td><td>Settling time</td></tr>
<tr><td>160</td><td>20</td><td>20</td><td>27</td><td>85%</td><td>4</td></tr>
<tr><td>320</td><td>20</td><td>20</td><td>52</td><td>92%</td><td>4</td></tr>
<tr><td>320</td><td>20</td><td>20</td><td>103</td><td>95%</td><td>5</td></tr>
<tr><td colspan="4">Compliance with WHO Guidelines for Drinking Water for turbidity (5 NTU)</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">Overall Induced Changes in the Water Quality</td></tr>
<tr><td colspan="6">A. Low Turbid Water Treatment by 160 mg Ovalbumin Coagulant</td></tr>
<tr><td colspan="4">Color (TCU): 13</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">Total Dissolved Solids (mg/L): 210</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">pH: 7.2</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">Alkalinity (mg/L): 50</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">B. Moderate Turbid Water Treatment by 320 mg Ovalbumin Coagulant</td></tr>
<tr><td colspan="4">Color (TCU): 13</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">Total Dissolved Solids (mg/L): 233</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">pH: 7.2</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">Alkalinity (mg/L): 50.1</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">C. High Turbid Water Treatment by 320 mg Ovalbumin Coagulant</td></tr>
<tr><td colspan="4">Color (TCU): 6</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">Total Dissolved Solids (mg/L): 345</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">pH: 7.2</td><td colspan="2">Comply</td></tr>
<tr><td colspan="4">Alkalinity (mg/L): 51</td><td colspan="2">Comply</td></tr>
<tr><td colspan="6">E. coli Reduction</td></tr>
<tr><td colspan="4">Input Variables</td><td colspan="2">Output Variables</td></tr>
<tr><td>Adsorbent dose (mg)</td><td>Contact time (min)</td><td>Initial E. coli count (colonies/ 10 ml)</td><td>E. coli Reduction%</td><td colspan="2">Final E. coli count (colonies/ 10 ml)</td></tr>
<tr><td>200</td><td>30</td><td>205</td><td>45%</td><td colspan="2">113</td></tr>
<tr><td colspan="4">Compliance with WHO Guidelines for Drinking Water (0)</td><td colspan="2">Does not comply</td></tr>
</table>

TR%, Turbidity Removal Rate %. NTU, Nephelometric Turbidity Unit. TCU, True Color Units.

To conclude, table 4.30 shows that the ovalbumin protein coagulant under the selected conditions can achieve high turbidity removal without affecting the specified water quality parameters. However, the dose chosen at the high turbid water sample (320 mg) was more effective because of the minimal changes observed in the overall water quality parameters than the low and medium turbid water samples. Additionally, preliminary pilot results showed that the ovalbumin protein reduced the presence of E. coli bacteria. However, this was only by 45%, which do not comply with the WHO Guidelines for Drinking Water that require the eradication of pathogenic microorganisms (no total coliforms or E. coli should be detected). Nevertheless, it can be concluded from those preliminary findings that the ovalbumin protein could be a potential eco-friendly coagulant for turbidity removal. Thus, to continue this study, further data and experimental designs are needed to investigate the efficiency of ovalbumin in removing various types of water treatment contaminants.

4.5. Comparison of Polyaluminum Chloride to Eco-Adsorbents/Coagulants

Polyaluminum chloride traditional coagulant was used as the control to compare turbidity removal and pathogenic microorganisms' destruction from the polluted water by the tested eco-adsorbents/coagulants. The main objective was to determine the dose of polyaluminum chloride that will optimally reduce those contaminants with minimum induced changes in the overall quality, as determined by color, TDS, pH, and alkalinity. Table 4.31 shows the efficiency of PAC in turbidity removal and E. coli reduction at the optimal identified dose.

Table 4.31: PAC Overall Profile in Enhancing Water Quality and Safety

Turbidity Removal					
Input Variables				**Output Variables**	
Adsorbent dose (mg)	**Contact time (min)**		**Initial Turbidity (NTU)**	**TR (%) Turbidity removal rate**	**Final Turbidity (NTU)**
	Mixing time	**Settling time**			
20	20	20	27	81%	5
20	20	20	52	92%	4
20	20	20	103	95%	5
Compliance with WHO Guidelines for Drinking Water for turbidity (5 NTU)				Comply	
Overall Induced Changes in the Water Quality					
A. Low Turbid Water Treatment by 20 mg PAC Coagulant					
Color (TCU): 5				Comply	
Total Dissolved Solids (mg/L): 177				Comply	
pH: 7				Comply	
Alkalinity (mg/L): 39				Comply	
B. Moderate Turbid Water Treatment by 20 mg PAC Coagulant					
Color (TCU): 8				Comply	
Total Dissolved Solids (mg/L): 202				Comply	
pH: 7				Comply	
Alkalinity (mg/L): 48.7				Comply	
C. High Turbid Water Treatment by 20 mg PAC Coagulant					
Color (TCU): 6				Comply	
Total Dissolved Solids (mg/L): 345				Comply	
pH: 7.4				Comply	
Alkalinity (mg/L): 50.2				Comply	
E. coli Reduction					
Input Variables				**Output Variables**	
Adsorbent dose (mg)	**Contact time (min)**	**Initial E. coli count (colonies/ 10 ml)**	**E. coli Reduction**	**Final E. coli count (colonies/ 10 ml)**	
200	30	205	99.5%	1	
Compliance with WHO Guidelines for Drinking Water (0)				Did not comply	

TR%, Turbidity Removal Rate %. NTU, Nephelometric Turbidity Unit. TCU, True Color Units.

To conclude, table 4.31 shows that the PAC under the selected conditions achieved desirable turbidity removal levels for all the turbid water samples with minimum induced changes in the overall water quality complying with the WHO Guidelines for Drinking Water. And, the preliminary pilot results showed that the PAC almost destroyed most of the E. coli bacteria by achieving around 99.5% E. coli reduction rate.

Further, table 4.32 shows the optimum performance of the tested eco-adsorbents/coagulants in this pilot study compared to the PAC efficiency in removing and reducing specific water contaminants: turbidity and pathogenic microorganisms.

Table 4.32: Comparison of PAC and Ecofriendly Materials in Contaminants Removal

Coagulants/ Adsorbents	PAC			Ovalbumin			Raw Banana Peels		Carbonized Banana Peels	Raw Eggshells	Carbonized Eggshells
1. Turbidity Removal											
Initial Turbidity (NTU)	27	52	103	27	52	103	27	103	27	103	27
Optimum Dose (mg)	20	20	20	160	320	320	40	20	80	160	40
Turbidity Removal %	81%	92%	95%	85%	92%	95%	84%	92%	63%	74%	81%
Final Turbidity (NTU)	5	4	5	4	4	5	4	4	10	26	5
2. Destruction of Pathogenic Microorganisms											
Selected Dose (mg)	200			200			200		200	200	200
E. Coli Reduction%	99.5%			45%			N.D		64%	OB	99%

N.D: Not Detected. OB: Over Bacterial Growth. NTU, Nephelometric Turbidity Unit.

By interpreting table 4.32, it can be concluded that the ovalbumin protein was the most efficient coagulant for turbidity removal compared to PAC. The ovalbumin was the only eco-adsorbent/coagulant that achieved desirable turbidity results at all water samples (low, medium, and high) while inducing minimal changes in the overall physio-chemical water quality as reflected by the determined parameters and within the WHO Guidelines for Drinking Water. However, it can be seen that the ovalbumin protein doses needed were at the highest (160 and 320 mg), which might represent an economic disadvantage compared to the PAC, which achieved the optimal results at a low dose (20 mg). Still, additional studies are needed to confirm the dose and optimize the experimental conditions. On the other hand, the carbonized eggshells was the only eco-adsorbent/coagulant that showed similar performance to PAC in pathogenic microorganisms' removal by achieving 99% E. coli reduction.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1. Overview of the Chapter

This pilot study aimed to investigate the efficiency of eco-friendly materials as low-cost water treatment methods to enhance WASH interventions in under-resourced communities and address the SDG6 targets related to safe drinking water. Preliminary initial screening was done for raw and carbonized banana peels, raw and carbonized eggshells, and ovalbumin protein. This chapter presents the main conclusions and recommends continuing research work to promote eco-friendly materials for domestic water treatment.

5.2. Effectiveness of Eco-Adsorbents/Coagulants from Agricultural Wastes in Water Treatment

The use of banana peels and eggshells eco-adsorbents/coagulants showed promising preliminary results for reducing turbidity, pathogenic microorganisms, and heavy metals contaminants from polluted water samples.

5.2.1. Water Treatment by Banana Peels

Based on this preliminary pilot study, water treatment by banana peels can be a cost-effective method as they were obtained from agricultural wastes. The preparation of the eco-adsorbents/coagulants was by low-cost and simple methods. Additionally, the following was noted:

- Banana peels acted as an efficient adsorbent for chromium and lead ions under optimum conditions. The raw and carbonized banana peels adsorbents achieved a 99.75% chromium removal at a dose of 20 mg and 100 mg. Similarly, 99.95% lead removal was achieved by the raw and carbonized banana peels at a dose of 20 mg and 100 mg. Additionally, the carbonization treatment of banana added chromium removal in high contamination levels.
- The optimum doses of raw banana peels for turbidity removal were 40 and 20 mg for the low and high turbid water samples. The induced changes in the overall water quality parameters as monitored by color, TDS, pH, and alkalinity were minimal, and all levels complied with the WHO Guidelines for Drinking Water.
- Treatment by raw banana peels was not effective. Still, the carbonization treatment enhanced the percent reduction of E. coli pathogenic microorganisms up to 63%.

These findings reflect on the potential of banana peels as a low-cost adsorbent for heavy metals removal. Still, its use as a coagulant for turbidity removal needs further optimization in terms of the applied dose and improving the coagulation conditions. Moreover, raw banana peels are better for turbidity removal, but they can be associated with microbiological water safety concerns without the carbonization treatment.

5.2.2. Water Treatment by Eggshells

Like the banana peels, eggshells obtained from agricultural wastes can be used as a simple and low-cost eco-adsorbent/ coagulant. Additionally, the following was noted:

- The eggshells adsorbent also achieved high chromium and lead removal rates under optimum conditions: 99.97% chromium removal at 60 mg and 94 mg adsorbent dose, and 99.95% lead removal at 60 mg adsorbent dose. Also, the carbonization treatment enhanced the chromium adsorption by the eggshells adsorbents in highly contaminated solutions.

- The optimum dose of carbonized eggshell for turbidity removal was 40 mg for the low turbid water sample. At this selected optimal dose, minimum induced changes were observed on the overall physio-chemical water quality as monitored by color, TDS, pH, and alkalinity. All reduced turbidity levels complied with the WHO Guidelines for Drinking Water. Still, eggshells acted as a poor coagulant without being enhanced with carbonization treatment.

- The raw eggshells eco-adsorbent/coagulant was not effective in reducing E. coli load but led to its overgrowth. However, the carbonized eggshells extract was able to achieve 99% E. coli reduction. Hence, the carbonized eggshells significantly reduced the E. coli count in contrast to the raw eggshells extract.

It can be inferred from those preliminary results that the eggshells adsorbent could be used as an effective, low-cost eco-adsorbent for chromium and lead removal. The carbonization treatment further significantly enhances the overall efficiency of the eggshells as an eco-adsorbent/coagulant. As a coagulant, raw eggshells was not effective for turbidity and pathogenic microbial removal. On the other hand, the carbonization of eggshells significantly influenced the removal of those contaminants.

5.3. Ovalbumin Protein as an Animal-Based Protein for Water Treatment

Preliminary results of experimenting with ovalbumin protein to determine its potential as a simple eco-adsorbent/coagulant showed the following:

- Ovalbumin protein could achieve higher turbidity removal comparable to using a traditional coagulant like poly-aluminum chloride.
- The optimum doses for turbidity removal achieved by the ovalbumin protein were 160 mg for the low turbid water sample and 320 mg for the moderate and high turbid water samples. The induced changes in the overall physio-chemical water quality parameters at the optimum doses for the low, moderate, and high turbid water samples were minimal. The induced changes were monitored by color, TDS, pH, and alkalinity, which complied with the WHO Guidelines for Drinking Water.
- The ovalbumin protein could have disinfection properties. Although only 50% E. coli reduction was achieved, it did not lead to bacterial overgrowth.

In general, this study reported that animal proteins such as ovalbumin could enhance water safety. This is by achieving high turbidity removal, preventing bacterial growth, and reducing the E. coli bacteria. However, the cost-effective methods for the isolation and purification process of ovalbumin from the egg whites should be further investigated to enhance its application in the developing countries.

5.4. Potential Usefulness of Ovalbumin Coagulant from Chicken Eggs in Low-Income Countries

The preliminary results of this pilot research showed that the ovalbumin protein extracted from the egg whites could have the advantage over chemical coagulants for water and wastewater treatment purposes. Natural coagulants, mainly from plant-based materials, such as Moringa Oleifrea, Cactus, Watermelon seeds, and others, have been recommended as inexpensive and less hazardous primary chemical treatment methods for contaminants removal. However, the studied natural plant-based coagulants have been perceived with significant barriers in commercialization related to economic and technical challenges. For example, it might be a constraint to produce vast quantities of water treatment coagulants from the plant seeds, and still, limited studies exist to address those barriers (Nimesha et al., 2021). Also, some natural coagulants, such as the watermelon seeds, were perceived with some concerns about their effect on the overall water quality parameters after treatment, such as increasing the pH and the organic matter if used at high doses (ROSELINE, 2014). On the other hand, due to the sustainability of natural coagulants and the public health benefits in terms of reducing the associated toxic effects with the conventional products, research efforts have been made to encourage modifying the studied natural-plant-based coagulants with the conventional coagulants (Nimesha et al., 2021; ROSELINE, 2014).

The ovalbumin protein of the chicken egg whites proposed by this pilot study could be an exciting product for future research in sustainable and eco-friendly water treatment technologies. This product might potentially be modified with other natural coagulants because of its high effectiveness in turbidity removal with enhancing the overall physical, chemical, and microbiological water quality. Besides the public health values of this novel natural material in substituting the harmful synthetic coagulants, this product can have potential usefulness to be applied in developing countries. Although the cost feasibility of ovalbumin protein was not studied in this research, egg products are generally low in cost due to the high availability of eggs globally. In addition, the FAO of the UN encouraged the consumption of eggs and egg products in low-income countries because of the plentiful production of chicken eggs globally (Forumon, 2018; Maloku et al., 2020). In addition, nowadays, the chicken eggs industry is considered somehow sustainable to the environment compared to other food industry sectors. The recent studies showed the reduced environmental footprint associated with the egg industry over the last 50 years (Maloku et al., 2020). This is another useful aspect that can encourage the commercialization of this novel natural coagulant extracted from the chicken egg whites. Thus, it can be concluded that the preliminary results of this pilot study showed positive findings associated with the ovalbumin protein as a natural coagulant which encourages future researches and studies on investigating further its applicability in low-income countries.

5.5. Recommendations for Future Work

The conclusions of this preliminary pilot research show a good potential for the use of ecofriendly materials and the potential of animal-based proteins as cost-effective alternatives to remove specific types of contaminants. Still, further studies are needed to confirm and elaborate on findings, applicability and cost effectiveness. Additional research work could address:

- Experimental design settings to enhance the removal of various contaminants such as heavy metals, turbidity, and pathogenic microorganisms. It was noticed that the dose and treatment time of the eco-adsorbents/coagulants for the trace metals removal were not comparable to the turbidity removal and E. coli reduction, which can be related to the variability in water chemistry. Thus, further studies can investigate the possibility of fixing the design settings for various contaminants removal from the polluted water sources. However, more data and new modeling directions would be favorable for computing all related chemical, physical and microbiological analyses on the same water samples source.

- Optimizing the design variables. Establishing optimization modeling for the selected factor designs such as the treatment time and eco-adsorbent/coagulant dose to obtain quicker and cheaper solutions for water treatment under emergency and poor community conditions.
- Explore the potential of designing a green-based polymer from carbonized eggshells and ovalbumin protein. This is to remove various contaminants from polluted water sources.
- Determine the cost effectiveness of such applications under emergency settings.

To conclude, the optimum eco-adsorbents/coagulants were the ovalbumin protein and carbonized eggshells. This is because those identified products achieved the best results compared to the control PAC as shown in table 4.32. The carbonized eggshells showed successful removal and reduction rates for all the tested contaminants in this study (chromium, lead, turbidity for the low turbid water, and E. coli bacteria) that complied with the WHO Guidelines for Drinking Water. The ovalbumin protein showed the best turbidity removal for the low, medium, and high turbid water samples with maintaining the water quality parameters within the WHO Guidelines for Drinking Water. However, the optimum dosages of ovalbumin were high compared to PAC, leading to additional costs. Thus, a continuation of this pilot study needs more data and modeling design to optimize the cost and performance of the ovalbumin-carbonized eggshells as a potential green based-polymer for water treatment.

APPENDIX 1

HEAVY METALS INITIAL SCREENING

Table A1.1: Trial Experiments Results. Co: Initial heavy metal concentration, ppm. Ce: Final heavy metal concentration, ppm. R%: Removal Rate. qe: adsorption capacity, mg/g.

1. Adsorbate: Cd	Co	Ce	R%	qe (mg/g)
Egg Raw	50	42.94	14.12	1.8356
Egg Carbonized	50	37.84	24.32	3.1616
Banana Raw	50	38.84	22.32	2.9016
Banana Carbonized	50	1.88	96.24	12.5112
2. Adsorbate : Cr	Co	Ce	R%	qe (mg/g)
Egg Raw	50	0.28	99.44	12.9272
Egg Carbonized	50	0.37	99.26	12.9038
Banana Raw	50	22.63	54.74	7.1162
Banana Carbonized	50	1.81	96.38	12.5294
3. Adsorbate : Fe	Co	Ce	R%	qe (mg/g)
Egg Raw	50	0.12	99.76	12.9688
Egg Carbonized	50	0.07	99.86	12.9818
Banana Raw	50	11.56	76.88	9.9944
Banana Carbonized	50	0.58	98.84	12.8492
4. Adsorbate : Pb	Co	Ce	R%	qe (mg/g)
Egg Raw	50	0.12	99.76	12.9688
Egg Carbonized	50	0.16	99.68	12.9584
Banana Raw	50	2.58	94.84	12.3292
Banana Carbonized	50	0.53	98.94	12.8622
5. Adsorbate : Zn	Co	Ce	R%	qe (mg/g)
Egg Raw	50	37.49	25.02	3.2526
Egg Carbonized	50	32.52	34.96	4.5448
Banana Raw	50	33.21	33.58	4.3654
Banana Carbonized	50	1.43	97.14	12.6282
1. Adsorbate : Cd	Co	Ce	R%	qe (mg/g)
Egg Raw	200	186.81	6.595	3.4294
Egg Carbonized	200	190.25	4.875	2.535
Banana Raw	200	182.96	8.52	4.4304
Banana Carbonized	200	189.59	5.205	2.7066
2. Adsorbate : Cr	Co	Ce	R%	qe (mg/g)

Egg Raw	200	171.02	14.49	7.5348
Egg Carbonized	200	173.26	13.37	6.9524
Banana Raw	200	166.41	16.795	8.7334
Banana Carbonized	200	147.31	26.345	13.6994
3. Adsorbate : Fe	Co	Ce	R%	qe (mg/g)
Egg Raw	200	113.86	43.07	22.3964
Egg Carbonized	200	159.27	20.365	10.5898
Banana Raw	200	127.32	36.34	18.8968
Banana Carbonized	200	107.35	46.325	24.089
4. Adsorbate : Pb	Co	Ce	R%	qe (mg/g)
Egg Raw	200	176.74	11.63	6.0476
Egg Carbonized	200	170.16	14.92	7.7584
Banana Raw	200	133.52	33.24	17.2848
Banana Carbonized	200	143.13	28.435	14.7862
5. Adsorbate : Zn	Co	Ce	R%	qe (mg/g)
Egg Raw	200	168.12	15.94	8.2888
Egg Carbonized	200	171.96	14.02	7.2904
Banana Raw	200	160.49	19.755	10.2726
Banana Carbonized	200	161.97	19.015	9.8878

APPENDIX 2

HEAVY METALS DOE

Table A2.1: Minitab 19 Plackett-Burman DOE for the raw and carbonized banana peels adsorbents. AD: Adsorbent Dose, mg. HMC: Heavy Metals Concentration (Chromium and Lead), ppm. CT: Contact Time, min.

StdOrder	RunOrder	PtType	Blocks	AD(mg)	HMC (ppm)	CT (min)
4	1	1	1	100	10	120
8	2	1	1	20	10	120
12	3	1	1	20	10	20
6	4	1	1	100	150	120
5	5	1	1	100	150	20
14	6	0	1	60	80	70
9	7	1	1	20	10	20
15	8	0	1	60	80	70
10	9	1	1	100	10	20
2	10	1	1	100	150	20
16	11	0	1	60	80	70
1	12	1	1	100	10	120
11	13	1	1	20	150	20
13	14	0	1	60	80	70
7	15	1	1	20	150	120
3	16	1	1	20	150	120

Plackett-Burman Design. Factors: 3. Replicates: 1. Base runs: 16. Total runs: 16.
Base blocks: 1. Total blocks: 1. Center points: 4

Table A2.2: Minitab 19 Box-Behnken DOE for the raw and carbonized eggshells adsorbents. AD: Adsorbent Dose, mg. HMC: Heavy Metals Concentration (Chromium and Lead), ppm. CT: Contact Time, min.

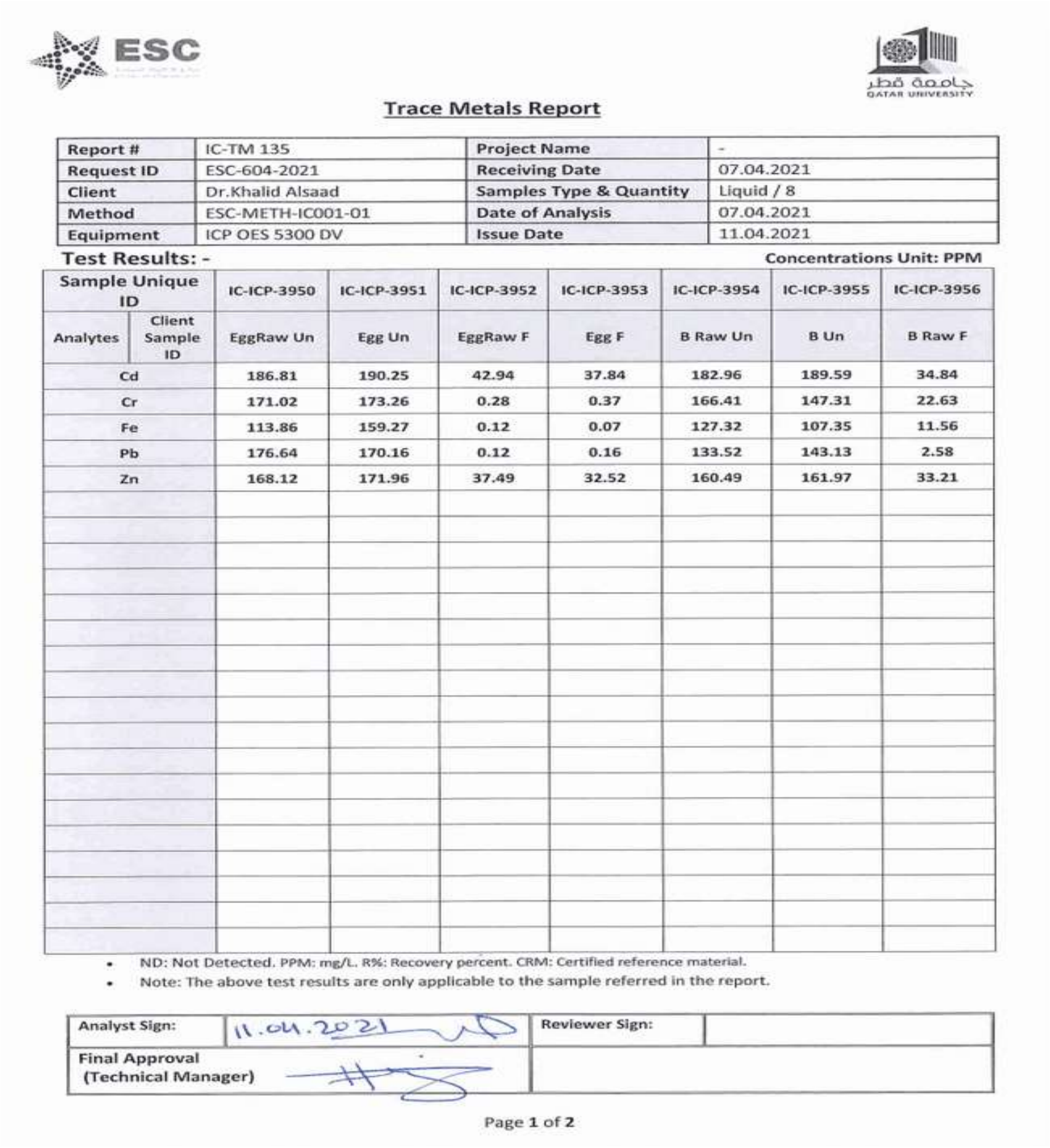
StdOrder	RunOrder	PtType	Blocks	AD(mg)	HMC (ppm)	CT (min)
2	1	2	1	100	10	70
9	2	2	1	60	10	20
4	3	2	1	100	150	70
1	4	2	1	20	10	70
3	5	2	1	20	150	70
10	6	2	1	60	150	20
13	7	0	1	60	80	70
6	8	2	1	100	80	20
7	9	2	1	20	80	120
16	10	0	1	60	80	70
5	11	2	1	20	80	20
14	12	0	1	60	80	70
8	13	2	1	100	80	120
11	14	2	1	60	10	120
12	15	2	1	60	150	120
15	16	0	1	60	80	70

Box-Behnken Design. Factors: 3. Replicates: 1. Base runs: 16. Total runs: 16. Base blocks: 1. Total blocks: 1. Center points: 4

APPENDIX 3

TRACE METALS REPORT

A3.1: Trace metals report for the screening experiments results



ESC

جامعة قطر
QATAR UNIVERSITY

Trace Metals Report

Report #	IC-TM 135	**Project Name**	-
Request ID	ESC-604-2021	**Receiving Date**	07.04.2021
Client	Dr.Khalid Alsaad	**Samples Type & Quantity**	Liquid / 8
Method	ESC-METH-IC001-01	**Date of Analysis**	07.04.2021
Equipment	ICP OES 5300 DV	**Issue Date**	11.04.2021

Test Results: - **Concentrations Unit: PPM**

Sample Unique ID		**IC-ICP-3950**	**IC-ICP-3951**	**IC-ICP-3952**	**IC-ICP-3953**	**IC-ICP-3954**	**IC-ICP-3955**	**IC-ICP-3956**
Analytes	**Client Sample ID**	**EggRaw Un**	**Egg Un**	**EggRaw F**	**Egg F**	**B Raw Un**	**B Un**	**B Raw F**
Cd		**186.81**	**190.25**	**42.94**	**37.84**	**182.96**	**189.59**	**34.84**
Cr		**171.02**	**173.26**	**0.28**	**0.37**	**166.41**	**147.31**	**22.63**
Fe		**113.86**	**159.27**	**0.12**	**0.07**	**127.32**	**107.35**	**11.56**
Pb		**176.64**	**170.16**	**0.12**	**0.16**	**133.52**	**143.13**	**2.58**
Zn		**168.12**	**171.96**	**37.49**	**32.52**	**160.49**	**161.97**	**33.21**

- ND: Not Detected. PPM: mg/L. R%: Recovery percent. CRM: Certified reference material.
- Note: The above test results are only applicable to the sample referred in the report.

Analyst Sign:	11.04.2021	**Reviewer Sign:**	
Final Approval (Technical Manager)			

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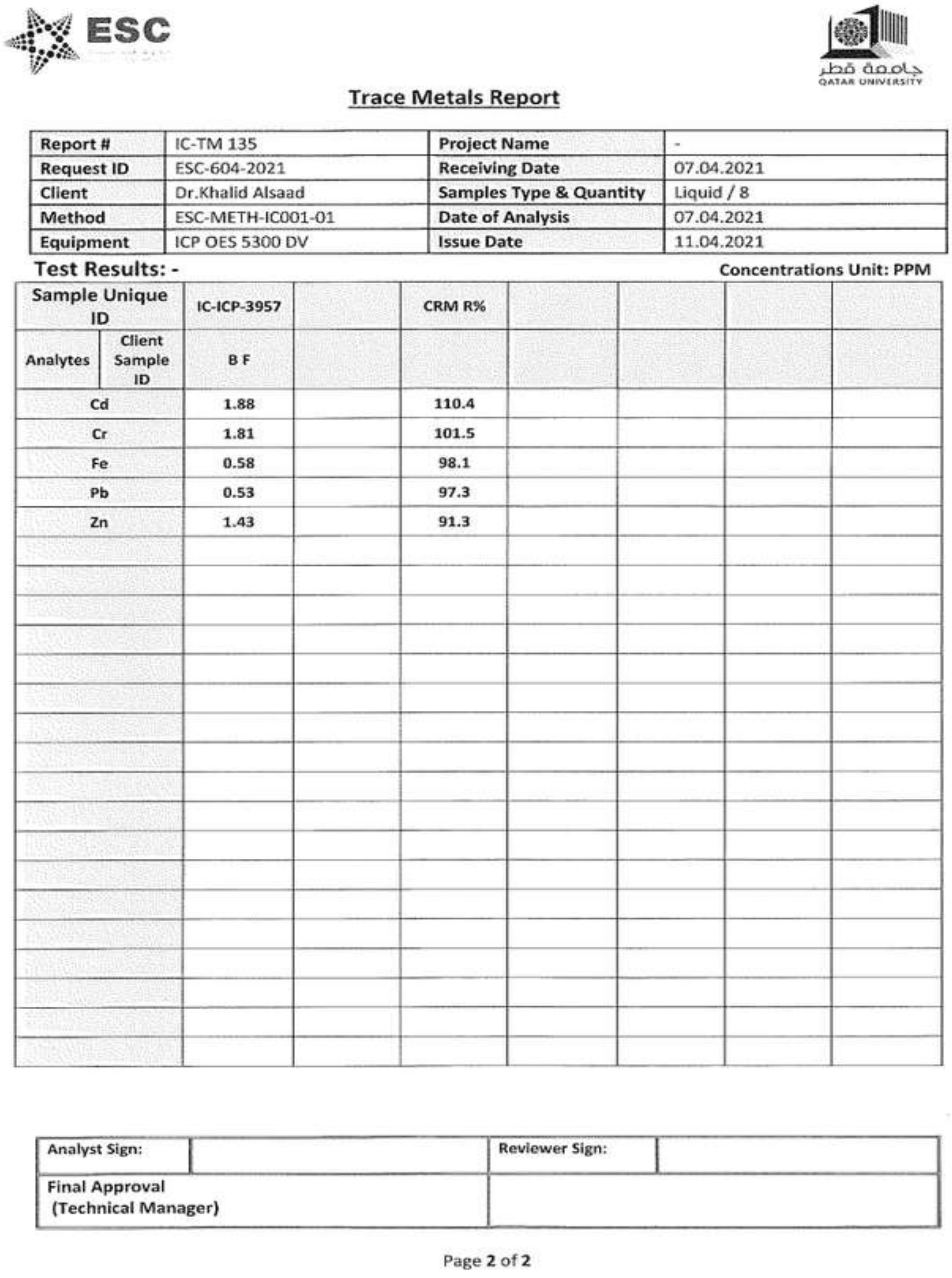

ESC

جامعة قطر
QATAR UNIVERSITY

Trace Metals Report

Report #	IC-TM 135	**Project Name**	-
Request ID	ESC-604-2021	**Receiving Date**	07.04.2021
Client	Dr.Khalid Alsaad	**Samples Type & Quantity**	Liquid / 8
Method	ESC-METH-IC001-01	**Date of Analysis**	07.04.2021
Equipment	ICP OES 5300 DV	**Issue Date**	11.04.2021

Test Results: -

Concentrations Unit: PPM

Sample Unique ID		**IC-ICP-3957**		**CRM R%**				
Analytes	**Client Sample ID**	**B F**						
Cd		**1.88**		**110.4**				
Cr		**1.81**		**101.5**				
Fe		**0.58**		**98.1**				
Pb		**0.53**		**97.3**				
Zn		**1.43**		**91.3**				

Analyst Sign:		**Reviewer Sign:**	
Final Approval (Technical Manager)			

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APPENDIX 4

DETAILED LABORATORY RESULTS OF THE PHYSIO-CHEMICAL PARAMETERS OF THE WELL WATER SAMPLES AFTER TREATMENT

Table A4.1: 27 NTU water samples treated with the raw banana peels coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
RB1	20	74.44	6.90	7.4	221	48.3	4.5
RB2	40	84.00	4.32	7.5	221	48.5	5.1
RB3	80	65.56	9.30	7.8	225	49	10.3
RB4	160	59.63	10.90	7.9	226.3	49	27
RB5	320	50.00	13.50	8.1	227	49.1	53.2
RB6	640	43.33	15.30	9.3	228	51	74.3

Table A4.2: 27 NTU water samples treated with the carbonized banana peels coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
CB1	20	39.63	16.30	7.1	200.3	49.3	3.4
CB2	40	51.11	13.20	7.2	201	49.3	4.1
CB3	80	63.70	9.80	7.2	201	50.5	4.9
CB4	160	59.26	11.00	7.3	205.7	51	23.5
CB5	320	49.63	13.60	7.3	207	51	31.2
CB6	640	42.22	15.60	7.4	207	53	51.4

Table A4.3: 27 NTU water samples treated with the raw eggshells coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
RE1	20	37.04	17.00	6.8	183	49.8	4.5
RE2	40	42.22	15.60	6.8	183.7	50.1	6.5
RE3	80	18.52	22.00	7	185	50.3	12.3
RE4	160	17.04	22.40	7	187	51	18
RE5	320	12.96	23.50	7	191.3	52	23.4
RE6	640	10.00	24.30	7	198	53	50.6

Table A4.4: 27 NTU water samples treated with the carbonized eggshells coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
CE1	20	47.41	14.20	7.1	200.3	49.3	3.4
CE2	40	81.40	5.02	7.2	201	49.3	4.1
CE3	80	61.85	10.30	7.2	201	51	4.9
CE4	160	53.70	12.50	7.2	206	51	23.5
CE5	320	47.78	14.10	7.3	210	51	27
CE6	640	39.63	16.30	7.4	210	52	49.5

Table A4.5: 27 NTU water samples treated with the ovalbumin protein coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
OV1	20	46.30	14.50	7.05	180	46.4	4
OV2	40	47.04	14.30	7.05	183	47.2	5.4
OV3	80	75.93	6.50	7.2	191.2	48	6.1
OV4	160	84.00	4.32	7.2	210	50	13.4
OV5	320	76.30	6.40	7.3	210.3	51	21.2
OV6	640	70.00	8.10	7.3	211	51	31.2

Table A4.6: 27 NTU water samples treated with the polyaluminum chloride coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
PAC1	20	82.59	4.70	7.1	177	39	5.1
PAC2	40	80.74	5.20	7.1	175	41	6.4
PAC3	80	77.41	6.10	7.2	186	43.5	10.9
PAC4	160	68.15	8.60	7.2	205	44	18
PAC5	320	65.56	9.30	7.2	207	45.7	28
PAC6	640	56.30	11.80	7.3	213	46	34.2

Table A4.7: 52 NTU water samples treated with the raw banana peels coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
RB7	20	76.73	12.10	6.8	230.1	47.5	5.4
RB8	40	78.27	11.30	6.9	230.1	47.5	7.3
RB9	80	78.65	11.10	7	231.4	48.6	15.1
RB10	160	85.29	7.65	7.1	231.4	48.6	26
RB11	320	83.75	8.45	7.3	234.1	49.3	55.3
RB12	640	74.04	13.50	7.43	235.2	50.7	71

Table A4.8: 52 NTU water samples treated with the carbonized banana peels coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
CB7	20	69.23	16.00	6.8	287	46	4.8
CB8	40	72.88	14.10	6.9	287	46	5.2
CB9	80	73.46	13.80	7.46	287	49.5	6.3
CB10	160	80.19	10.30	7.46	290.5	50.3	16.5
CB11	320	81.35	9.70	7.7	290.5	52.1	46
CB12	640	74.42	13.30	7.9	305.7	53.2	62.3

Table A4.9: 52 NTU water samples treated with the raw eggshells coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
RE7	20	32.50	35.10	6.9	215	50.3	4.93
RE8	40	35.96	33.30	6.9	225.3	50.5	4.93
RE9	80	40.00	31.20	7	311.3	51.1	5.06
RE10	160	62.88	19.30	7.02	315.3	51.1	5.46
RE11	320	42.88	29.70	7.1	318	53.1	6.32
RE12	640	37.50	32.50	7.1	318	54.7	6.7

Table A4.10: 52 NTU water samples treated with the carbonized eggshells coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
CE7	20	63.27	19.10	7.2	286	49	4.3
CE8	40	69.81	15.70	7.2	286.5	49	4.32
CE9	80	86.40	7.07	7.2	287	49.5	5.7
CE10	160	90.60	4.89	7.2	295.3	50.15	26.2
CE11	320	81.67	9.53	6.91	297	50.2	30.1
CE12	640	80.15	10.32	7.2	297	53.1	43

Table A4.11: 52 NTU water samples treated with the ovalbumin protein coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
OV7	20	56.73	22.50	6.95	200.5	47.3	5.3
OV8	40	67.12	17.10	7.05	209	48	5.3
OV9	80	74.23	13.40	7.1	215.3	48.7	5.6
OV10	160	85.58	7.50	7.1	233	50.1	8.3
OV11	320	91.92	4.20	7.2	233	50.1	12.94
OV12	640	85.00	7.80	7.2	235.3	51.3	15.6

Table A4.12: 52 NTU water samples treated with the polyaluminum chloride coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
PAC7	20	91.73	4.30	7.	201.5	48.7	7.6
PAC8	40	83.46	8.60	7.1	213	48.8	7.9
PAC9	80	81.35	9.70	7.2	213.7	49.3	11.2
PAC10	160	78.27	11.30	7.3	225	49.35	15.3
PAC11	320	76.15	12.40	7.3	227.2	50.1	21
PAC12	640	75.38	12.80	7.3	227.2	50.3	30.3

Table A4.13: 103 NTU water samples treated with the raw banana peels coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
RB13	20	91.73	4.30	7.1	311.5	48.3	4.5
RB14	40	83.46	8.60	7.1	313	49.2	10.3
RB15	80	81.35	9.70	7.2	313.7	49.2	24.5
RB16	160	78.27	11.30	7.2	325	51	49.5
RB17	320	76.15	12.40	7.2	327.2	52.3	79.1
RB18	640	75.38	12.80	7.3	327.2	53	86.1

Table A4.14: 103 NTU water samples treated with the carbonized banana peels coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
CB13	20	83.37	17.13	7.1	311.7	48.2	3.37
CB14	40	86.50	13.90	7.1	312	49.5	3.9
CB15	80	87.48	12.90	7.13	312	50.3	27.19
CB16	160	87.09	13.30	7.62	353	53	37
CB17	320	84.76	15.70	8.1	409.8	54	46.8
CB18	640	84.66	15.80	9.14	518.7	54.5	73.9

Table A4.15: 103 NTU water samples treated with the raw eggshells coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
RE13	20	51.17	50.30	6.87	337.8	45.9	3.6
RE14	40	61.07	40.10	6.9	339	46.1	3.6
RE15	80	65.92	35.10	6.9	339	46.5	3.68
RE16	160	73.20	27.60	7.1	341	48.4	3.8
RE17	320	60.87	40.30	7.21	345	51	4.24
RE18	640	59.71	41.50	7.21	357	52.3	4.8

Table A4.16: 103 NTU water samples treated with the carbonized eggshells coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
CE13	20	84.37	16.10	6.9	343	47.7	3.91
CE14	40	87.18	13.20	7.05	343.7	48.9	4.53
CE15	80	88.64	11.70	7.1	345	49.3	5.47
CE16	160	86.60	13.80	7.15	345	49.7	5.47
CE17	320	85.44	15.00	7.2	345	51.2	5.71
CE18	640	84.17	16.30	7.2	346.1	52	6

Table A4.17: 103 NTU water samples treated with the ovalbumin protein coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
OV13	20	79.51	21.10	7.08	315	49	4.32
OV14	40	83.40	17.10	7.1	315	49.3	4.9
OV15	80	86.21	14.20	7.1	332	49.2	5.23
OV16	160	90.75	9.53	7.1	333.75	49.5	5.5
OV17	320	95.20	4.94	7.19	336.7	50.3	6.31
OV18	640	94.50	5.67	7.21	339	50.5	7.1

Table A4.18: 103 NTU water samples treated with the polyalumunium chloride coagulant

Code No.	Dosage (mg)	Turbidity Removal (%)	Turbidity Level (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L)	Color (TCU)
PAC13	20	95.44	4.70	7.38	345	50.2	5.7
PAC14	40	94.85	5.30	7.4	345	50.3	12.7
PAC15	80	89.22	11.10	7.35	350.3	51	13.4
PAC16	160	88.54	11.80	7.3	359	51	15.2
PAC17	320	88.06	12.30	7.4	363	52	17.3
PAC18	640	86.31	14.10	7.41	364.1	52.4	17.9

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