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1. Chapter 1: Present and Justify a Problem and Solution Requirements.

Introduction

Egypt confronts significant obstacles referred to as "Grand Challenges," **illustrated in Figure 1.1**. These challenges contribute to the decline of its economic, scientific, cultural, and technological foundations. Egypt aims to address these issues as part of its Vision 2030 plan, with hopes of achieving solutions by 2030.

Figure 1.1: Egypt's Grand Challenges

Recycling garbage and waste can significantly reduce pollution in our air, water, and soil while providing economic benefits. Proper waste management can prevent harmful emissions from landfills, such as methane and carbon dioxide, thus combating climate change. Additionally, reducing pollution through recycling efforts can improve public health, particularly by mitigating respiratory issues caused by air pollution. By enhancing waste management and recycling systems, we can also manage and increase the sources of clean water, ensuring sustainable water supplies for all communities and meeting the rising demand due to increasing population. Furthermore, improving the uses of arid areas can expand Egypt's industrial and agricultural base, transforming these regions into productive assets.

Egypt Grand Challenges

Recycle Garbage and Waste for Economic and Environmental Purposes

Egypt faces a serious problem of waste management. Rapid population growth and urbanization play a primary role in this problem. Recent studies indicate that the country's waste production is growing at an alarming rate, currently increasing by about 3.4% annually, this is mainly because Egypt's population grows by around 2 million people each year. This increase in waste generation is beyond Egypt's recycling capabilities. The global standard of recycling is 40-60% of waste, **as shown in Figure** 1.2. Unfortunately, Egypt's infrastructure is still undeveloped enough to achieve this percentage, it only recycles about 15-20% of its waste. The insufficient infrastructure makes it harder for the country's management systems. In addition, many of them are either improper or illegal.

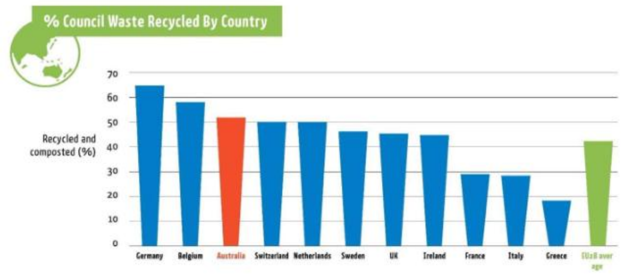


Figure 1.2: Global rate of recycling.

Egypt currently has about 30 formal recycling sites, which are not enough to process the massive amount of solid waste being generated, which is estimated to be 26 million tons of solid waste and increasing, **as shown in Figure** 1.3. Moreover, despite efforts to establish waste sorting and recycling facilities, the country lacks a comprehensive waste collection and segregation system. Only about 9% of Egypt's households have access to formal recycling services, leaving the majority of waste either burned or dumped into illegal landfills. Additionally, a lack of public awareness and educational campaigns means that many Egyptians are unaware of the benefits of recycling, with participation rates in recycling programs hovering around 8-10%. This combination of factors underscores the urgent need for Egypt to

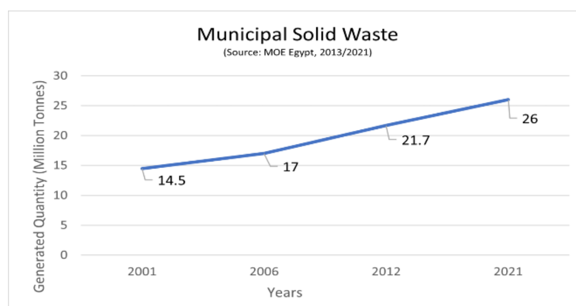


Figure 1.3: Solids wastes in Egypt.

develop a more robust and efficient recycling system to address the growing waste crisis.

Causes

1. **Rapid Growth in Waste Generation**

Egypt is currently experiencing huge urbanization and population growth. This growth is accompanied by an increase in waste generation. Now Egypt produces about 26 million tons of solid waste annually, expected to increase to 50 million tons by 2030 if the problem isn't solved. The population is expected to increase to 160 million by 2050 with the rate of urbanization expected to increase to 69%, **as shown in Figure** 1.4, this will increase the waste produced by the urban areas and not being recycled.

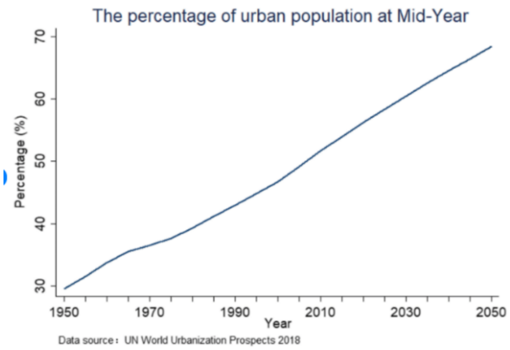


Figure 1.4: Urbanization rate in Egypt.

2. **Insufficient Waste Management Infrastructure**

The lack of proper infrastructure is a primary cause of the problem of Egypt's recycling challenges. The country generates around **26 million tons of waste annually**, but only **12-15%** of this waste is recycled, **as shown in Figure** 1.5. Most of the waste is being dumped in dumpsites or landfills. Most of these landfills aren't equipped with advanced recycling technologies. A 2021 report indicated that about **3,000 illegal dumpsites** are spread across the country, contributing to environmental decay, and limiting the recovery of recyclable materials. This undeveloped infrastructure has improper funding, which has led to has led to inefficient waste collection and processing systems. There are illegal garbage collectors who manage to recycle up to **80%** of the waste they collect, but due to the absence of formal recognition and support, they are unable to scale up their efforts.

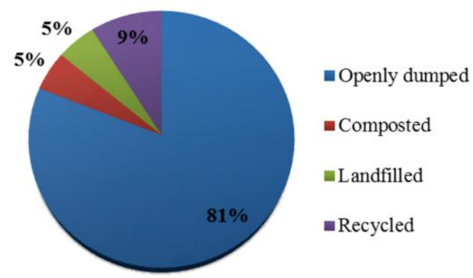


Figure 1.5: Fate of waste in Egypt.

3. **Weak Regulatory Framework**

Few government policies encourage recycling, and existing regulations are not enforced effectively. For example, only **1-3%** of Egypt's hazardous waste is safely treated, and the rest is often improperly removed, including toxic medical waste and industrial by-products. There is no national recycling law, and the recycling programs are primarily managed by local governments with limited capacity to enforce policies or expand infrastructure.

In addition, there is a low awareness of the importance of recycling among people. Surveys reveal that **60% of Egyptians** do not engage in any recycling practices, and many are unaware of the environmental and economic benefits of recycling. Furthermore, there are very few public recycling bins or collection services, especially outside urban centers, which makes it difficult for people to recycle even if they are willing to do so.

Impacts

1. **High Organic Waste Composition**

The huge amount of organic waste in Egypt is considered a serious problem. **As shown in Figure** 1.6, according to EEAA, about 56% of Egypt's total solid waste is organic, equivalent to around 45 million tons generated annually. Organic waste has many forms, for example, food scraps, agricultural residues, and yard waste. This waste is left in landfills, thus producing methane gas. Methane gas is considered a greenhouse gas. According to the World Bank, Methane gas is about 25 times more harmful than carbon dioxide over a 100-year period. If this organic waste is recycled, there will be less methane which will significantly reduce greenhouse gas emissions.

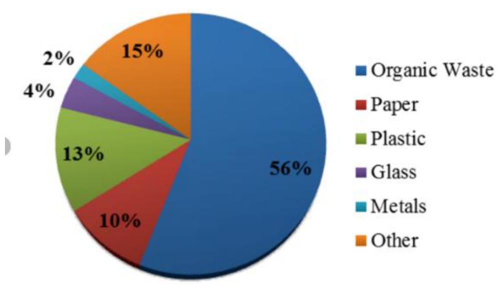


Figure 1.6: Composition of solid waste in Egypt.

2. **Environmental and Public Health Concerns**

Waste management in Egypt results in significant environmental health problems. Studies reveal that improper dumping of waste is linked to **respiratory diseases, waterborne illnesses,** and other health problems. Around 20% of the total waste in Egypt is considered hazardous and very dangerous, including medical waste, electric and electronic waste, and industrial by-products, which add additional risk of not being handled well. The results of poor recycling in Egypt include soil contamination, air pollution from burning waste, and the degradation of natural habitats. By increasing the recycling rate, Egypt will experience fewer problems and a more friendly environment.

3. Economic Loss

There is a lot of economic loss due to the lack of recycling in Egypt. The 90 million tons of Egypt contains valuable materials such as plastics, metals, and organic waste, which could generate an estimated **1.5 billion dollars per year**.

The management system of waste in Egypt affords high costs for landfill operations. An estimated cost of **2.5 billion dollars annually is** due to poor waste handling practices, environmental damage, and healthcare costs related to pollution. Since the recycling sector in Egypt is still undeveloped, it adds additional costs for unemployed people. Increasing the recycling industry will add thousands of job opportunities. For example, the informal recycling sector already employs over **1 million people**, but better infrastructure could increase this significantly.

In addition, Factories in Egypt import raw materials which costs billions of dollars. Plastic is an example of these raw materials, in 2020, Egypt spent over 2 billion dollars to import plastic only. This cost could be reduced by recycling the existing plastic waste. All these losses together emphasize the need to improve the recycling process in Egypt to reduce the financial strain.

Addressing and Reducing Pollution Fouling Our Air, Water, and Soil

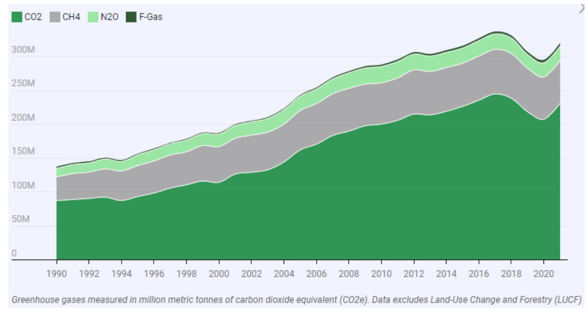


Figure 1.7: Greenhouse emissions in Egypt.

Pollution is the introduction of harmful materials into the environment. These harmful materials are called pollutants. Air pollution has been a problem for Egyptians for decades, particularly in large cities such as Cairo. Egypt is the 9th country in the world according to the level of air pollution in 2023. Pollution in Egypt has many forms including air, soil, and water pollution. This pollution threatens many sectors in Egypt including agriculture, health, and others.

Air pollution is an obvious problem, especially in industrial cities. **As shown in Figure 1.7,** The amount of greenhouse gases in Egypt is increasing, which indicates that air pollution is getting more serious every day. According to the World Health Organization (WHO), Cairo is one of the most polluted cities in the world in terms of air quality, with particulate matter (PM2.5) levels frequently exceeding safe limits.

Water pollution is also an important problem. The Nile River, Egypt's main source of drinking water, is severely polluted with industrial wastes, agriculture runoff, and untreated sewage. According to the Egyptian Environmental Affairs Agency (EEAA), a significant portion of the Nile is contaminated, impacting drinking water quality and reducing agricultural productivity in the Nile Delta, which is the most important agricultural area.

Soil pollution is another serious problem due to the wide use of fertilizers and chemical pesticides. The Food and Agriculture Organization (FAO) highlights that soil degradation in Egypt threatens food security as arable land is gradually lost to pollution.

Causes

1. **The Quality of Diesel Fuel**

Most of the pollution, specifically air pollution, in cities, comes from the burning of fossil fuels as means of transport. According to the Egyptian

Environmental Affairs Agency (EEAA), diesel-powered vehicles account for around 70% of total vehicular emissions in major cities like Cairo. Diesel fuel in Egypt usually contains a relatively high amount of Sulfur. The burning of diesel fuel with Sulfur in it leads to the reaction of Sulfur with Oxygen in the air, resulting in the evolution of Sulfur dioxide (SO_2), which is considered a greenhouse gas that leads to an increase in air pollution.

During rain, some of this sulfur dioxide gas dissolves in the water droplets, leading to the formation of acidic rains. When these rains fall on waterways, they cause water pollution. If this waterway is a river or a groundwater source, drinking this water can be poisonous. When watering the soil with polluted water, it causes soil pollution and thus affects the quality of the crops.

2. **The Improper Disposal of Plastic Waste**

According to the Egyptian Ministry of Environment, the country generates 90 million tons of waste annually, just 20% of it being properly treated or recycled. The remaining 80% is usually dumped or managed in open landfills. This huge amount of waste leads to the spread of pollutants that cause soil and water contamination.

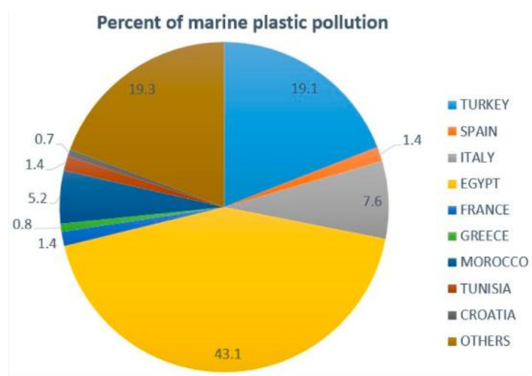


Figure 1.8: Percentage of plastic leakage into the Mediterranean Sea.

One of the most polluting wastes is plastic. According to the United Nations Environment Program (UNEP), Egypt produces about 970,000 tons of plastic waste every year. 42,000 tons of them are being dumped in the Mediterranean Sea, which makes Egypt the largest polluter in the Mediterranean countries, **as shown in Figure 1.8**. This plastic threatens marine life because large items of plastic can capture and entangle marine mammals and fish and stop them from escaping, usually leading to starvation, injury, and predator vulnerability. This is why plastic causes water pollution.

3. **Industrial Emissions**

Industry in Egypt has been growing exponentially. The factories have waste that is often harmful to the environment. According to the Egyptian Environmental Affairs Agency (EEAA) in 2023, industrial activities are responsible for approximately 30% of the total air pollution in Egypt. Some harmful gases, such as sulfur dioxide (SO_2), Carbon dioxide (CO_2), Nitrogen oxides, and many others. These gasses decrease the quality of the air and cause air pollution.

Another form of pollution caused by factories is water pollution. Also, according to EEAA, 60% of industrial facilities in Egypt don't treat their wastewater before dumping it into the seas or the Nile River. This causes contamination in the drinking water in the Nile River or even destroys marine life in the seas.

Impacts

1. **The Health Toll of Air Pollution**

Air pollution, in all forms, affects the public health obviously. It is responsible for more than 6.5 million deaths each year globally, a number that has increased over the past two decades. Egypt faces severe health problems because of air pollution. According to the World Health Organization database, air pollution-related illnesses responsible for premature mortality in Egypt in 2016 included heart disease (57.9%), stroke (17.7%), and pulmonary and lower respiratory diseases and cancer (24.4%).

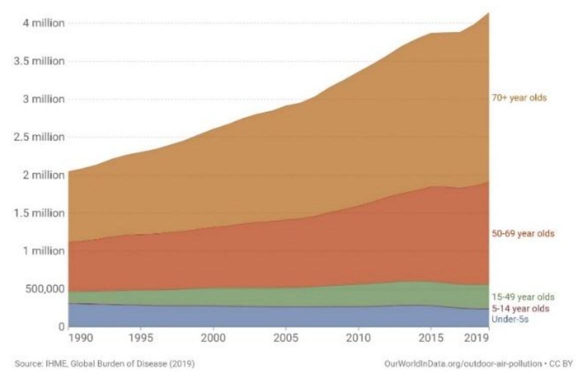


Figure 1.9: Deaths caused by air pollution.

The impacts of air pollution on Egyptian health aren't limited to just illness, sometimes the disease develops leading to death. According to the Institute for Health Metrics and Evaluation, about 12% of deaths in Egypt, which is counted to be 4.2 million people, in 2019 because of air pollution, **as shown in Figure** 1.9. This percentage is more than the average death caused by air pollution in the world, which is about 11%. That's why it's a serious impact that should be considered.

2. **The Economic Burden of Air Pollution in Egypt**

Pollution causes economic loss due to its consequences. According to the World Bank in 2019, Pollution in Egypt costs about 47 billion dollars annually, which is approximately 4.4% of the country's Gross domestic product (GDP). For example, an estimated amount of 22 billion dollars is being paid for pollution-caused diseases including surgical operations for cardiovascular diseases and others.

Evidence is that according to the World Health Organization (WHO), air pollution-related health issues are responsible for approximately 40,000 premature deaths annually in Egypt.

According to The Food and Agriculture Organization (FAO), There are economic losses of about 2 billion dollars annually in agriculture due to reduced crop quality, where pollution contributes to the large cause of it. Also, according to the EEAA report in 2020, air pollution leads to increased healthcare costs, with 30% of hospital admissions in urban areas linked to air quality problems.

3. **Effect of Water Pollution on Marine Ecosystems**

Rising pollution levels in waterways have severe consequences on marine life. Increasing the percentage of pollutants like heavy metals or agricultural wastes, containing fertilizers and pesticides, can kill some fish species, thus decreasing the biodiversity of marine life. The United Nations Environment Program (UNEP) in 2020 reports that nearly 30% of the native species to the Nile are threatened due to pollution and habitat degradation. According to the WHO in 2021, fertilizers and pesticides specifically have negative results on the food of the fish as they allow harmful blooms to grow thus consuming oxygen and decreasing its percentage in water bodies.

Improving Uses of Arid Areas

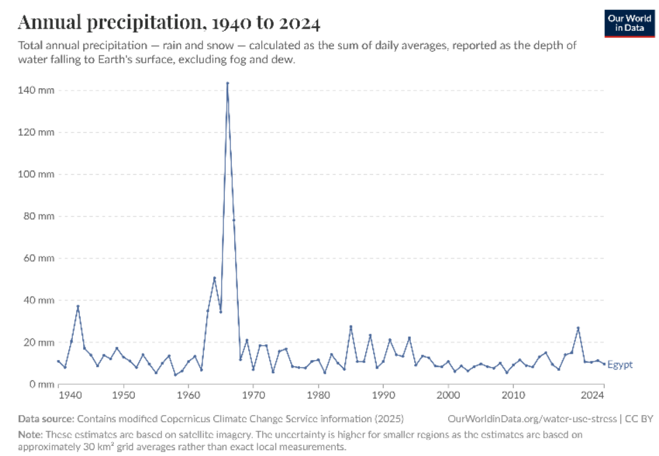


Figure 1.10: Total annual precipitation calculated as the sum of daily

According to the national park service of the US, arid areas receive less than 25 centimeters of annual rain. Often, arid areas have little vegetation and very loose soil with erosion being the main factor shaping its surface.

According to literature, Egypt's lands are entirely considered drylands. 86% of such land is considered Hyper-arid, receiving less than 50 millimeters of rain annually. The other 14% is arid.

According to the International Commission on Irrigation & Drainage (ICID), Alexandria has the most rainfall in all of Egypt with only 20 centimeters annually, while Cairo receives 2.5 centimeters. Additionally, the rainfall occurs only in winter, and is mostly in the form of scattered showers, making it unsuitable as a dependable source of water. **As shown in Figure 1.10**, Egypt only got 1 centimeter of rain in the year 2024.

Between 1976 and 2000, Egypt warmed at an average rate of 0.2-0.8$°C$ per decade. Prior research notices that such an increase in temperature leads to the increase of rainfall. Yet it also does lead to an increase in evapotranspiration, which is the loss of water both from evaporation and transpiration. It's expected that the loss of water from evapotranspiration is higher than the rainfall gained by rainfall.

Causes

1. **Stress on water resources**

As shown in Figure 1.11, Egypt's population has increased by 20 million in the time span between

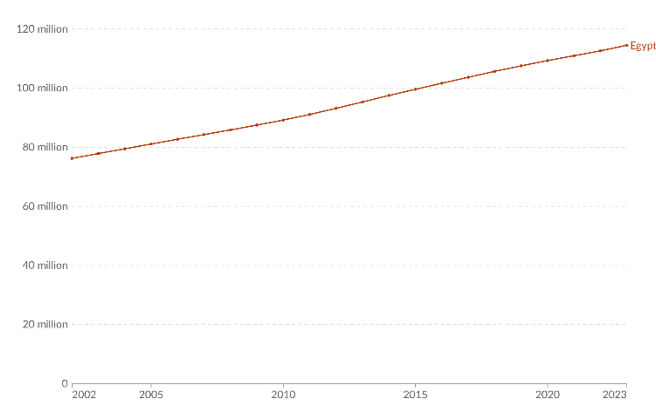


Figure 1.11: Egypt's population since 2013

2013 and 2023. Such a high growth rate has led to increased water consumption which stresses Egypt's water resources. Previous literature estimates that deserts will continue to enlarge over the next century, covering 10% more of earth's surface. This could lead to the drying of certain water resources in Egypt, such as oases, furthering the problem's severity.

2. **Over-irrigation**

Irrigation accounts for approximately 85% of Egypt's water consumption. The percentage is large mainly due to terrible irrigation methods. Mainly, Egyptians use methods such as flood irrigation, while much more efficient methods such as drip and sprinkler irrigation aren't used. While this does eliminate aridity in the areas irrigated, it wastes Egypt's water resources, making it tougher to decrease aridity in other locations.

Impacts

1. **Soil erosion**

As stated in the overview, aridity leads to decreased plant growth. Since plants, specifically trees, act as wind breaks, their absence can increase the effect wind has on eroding the soil. Additionally, wind increases transpiration from plants, which exacerbates aridity, leading to a negative feedback loop. Wind can also lead to the formation of sand dunes, which shift over moderate periods of time. Sometimes, they can encroach on civilized locations. Additionally, the absence of vegetation also allows rainfall to fall directly onto the soil, destroying the structure of, particularly, topsoil.

2. **Wildfires**

As more trees and plants in farms die due to aridity, dry biomass forms over large areas of farmland. Dry biomass is known for its flammability, which makes it a threat as wildfire could emerge. On a large scale, this also causes climate change and urban congestion, as people will need to move in emergencies from affected areas.

3. **Decreased Biodiversity**

According to a convention by the United Nations, one-fifth of all lands might experience sudden ecosystem transformations due to aridity by the end of the century. This could increase costs for animal farms, as special accommodation would have to be implemented such as cooling systems.

Managing and Increasing the Sources of Clean Water

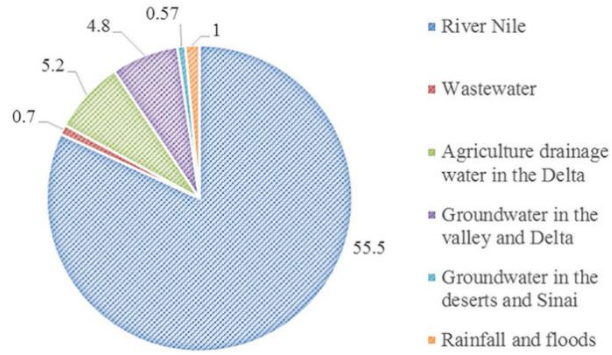


Figure 1.12: Egypt's Main Water Resources

Egypt is weakened by a significant water scarcity problem. Egypt's annual renewable water resources are approximately 60 billion cubic meters, primarily from the Nile River. However, the country's water demands have increased to about 114 billion cubic meters per year, resulting in great deficiency. This issue is partially reduced by recycling approximately 34 billion cubic meters of water annually. However, a significant gap remains.

The Nile River contributes 55.5 billion cubic meters annually, **as shown in Figure 1.12**, accounting for about 79.3% of Egypt's total water resources. Groundwater resources in the Nile Valley and Delta are estimated at 6.1 billion cubic meters per year, with the potential to increase to 7.5 billion cubic meters without compromising the reserves. Rainfall is minimal due to the arid climate, contributing to approximately 1.3 billion cubic meters annually. Agricultural drainage water provides an annual average of about 12 billion cubic meters, with approximately 5.7 billion cubic meters currently being reused. Treated wastewater contributes around 2.5 billion cubic meters annually, which can be utilized for irrigation if it meets international health standards.

A significant portion of Egypt's water resources is allocated to agriculture, which consumes about 85% of the total water resources. This heavy reliance on water-intensive agricultural practices exacerbates the water scarcity issue.

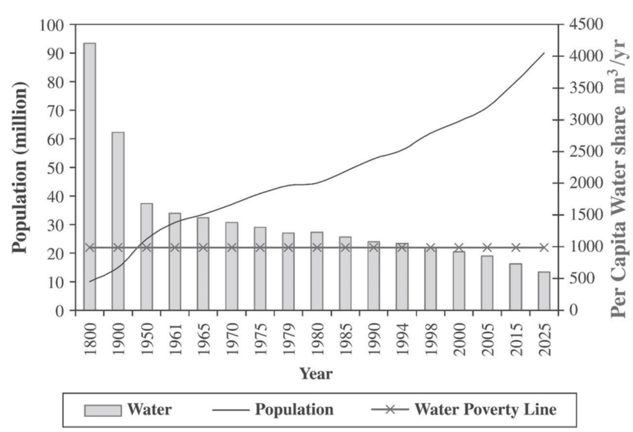


Figure 1.13: Population Growth and Per Capita Water Share in Egypt

Causes

1. **Population Growth**

Egypt's population has been steadily increasing, leading to a higher demand for water, **as shown in Figure 1.13**. An adult male requires about 3.7 liters of water daily, while an adult female needs approximately 2.7 liters. This growing demand exacerbates the strain on the already limited water resources.

2. **Pollution of the Nile River**

The Nile River receives wastewater from 67 agricultural drains, with only 10 meeting Egyptian regulations for acceptable wastewater discharge. Major pollutants include heavy metals from industrial, agricultural, and domestic effluents. This pollution not only degrades water quality but also poses significant health risks to the population.

3. **Excessive Water Wastage in Economic Activities**

Approximately 85% of Egypt's water resources are utilized for agriculture, **as shown in Figure 1.14**, often through inefficient irrigation systems leading to significant water loss. The reliance on traditional irrigation methods, such as flood irrigation, results in substantial water wastage. Modernizing these systems could improve water use efficiency and help mitigate scarcity.

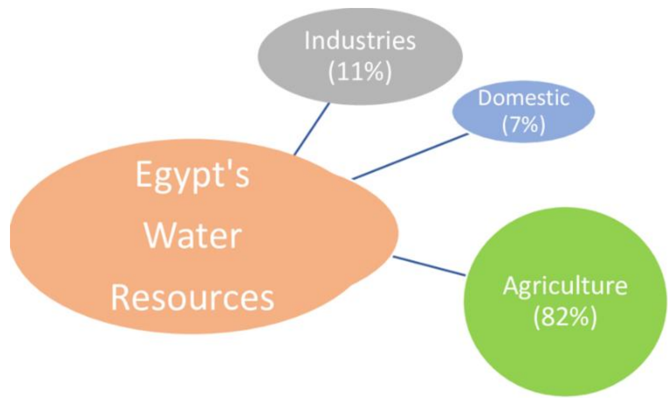


Figure 1.14: Water consumption by sector in Egypt.

Impacts

1. **Health Issues**

While access to water Is almost universal and reliable in urban areas, a large number of households remain disconnected from the water network in rural areas and urban slums. 7.3 million people are deprived of access to safe water, of whom 5.8 million live in rural areas and 1.5 million in urban areas. Lack of access to safe drinking water and proper sanitation facilities, as well as poor hygiene, contribute to the spread of diseases, which has a significant and negative impact on children's health and nutrition. In Egypt, diarrhea is the second leading cause of death among children under the age of five. Most deaths associated with diarrhea in children are due to dehydration caused by the loss of large amounts of water and electrolytes.

Statistics indicate that between 3,500 and 4,000 children under the age of five die from diarrhea every year.

2. **Economic Challenges**

Water scarcity hampers agriculture, which contributes 11.3% to Egypt's GDP and represents 28% of all jobs. In Upper Egypt, over 55% of employment is related to agriculture. The water deficit leads to a food gap exceeding 10 billion dollars, necessitating substantial food imports to meet domestic demand.

Increasing the Industrial and Agricultural Base of Egypt

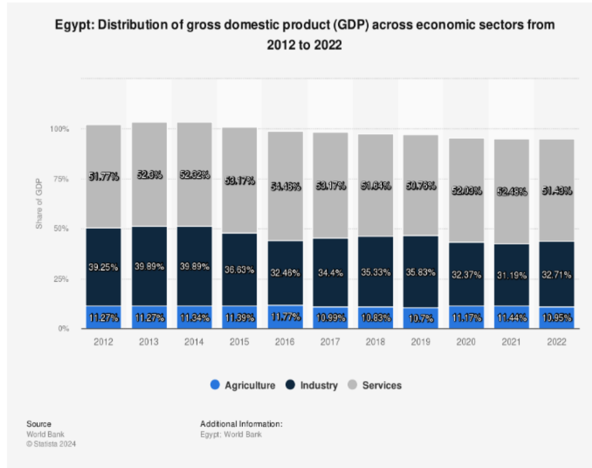


Figure 1.15: Egypt's GDP by economic sector.

Egypt's industrial sector plays a vital role in its economic development, contributing approximately 15% of the gross domestic product (GDP), **as shown in Figure 1.15**, and employing millions of workers. However, Egypt confronts many challenges in its industrial development including low productivity, high energy costs, regional disparities, and environmental degradation. Agriculture is a major component of the Egyptian economy, contributing 11.3% of the country's GDP. The agricultural sector represents 28% of all jobs, whereas more than 55% of jobs in Upper Egypt are related to agriculture.

Egypt relies heavily on the Nile River for irrigation purposes, and water scarcity poses a major challenge, as Egypt’s total income from Nile water reaches 55.5 billion cubic meters annually. The weight of water consumption was as follows, agricultural needs are 54.4 billion cubic meters annually, drinking needs are 2.9 billion cubic meters annually, and industry needs are 3.9 billion cubic meters annually. Moreover, Egypt’s total land area is estimated to be 995,450 km^2, but only 3.6% actual area is used for agricultural purposes.

Factories may suffer from a lack of water needed for cooling operations or for the production processes themselves. They can contribute to farmland degradation, where they can pollute the surrounding environment with toxic chemicals that destroy soil fertility, decreasing crop production. This may also contaminate food. Factories can also pollute water by dumping contaminated water, gases, chemicals, heavy metals, or radioactive materials, mainly because dumping such materials is cheaper than treating them. In addition, many industries rely on locally produced agricultural raw materials, and if farmland deteriorates, the production of these materials may decline, impacting the associated processing industries.

Causes

1. Urban Encroachment

Urban encroachment poses a great danger to productive agricultural lands, despite a law prohibiting construction on productive agricultural lands. There were no significant preventive measures against most encroachment cases on productive agricultural land. This leads to an annual loss of 20,000 to 100,000 acres of agricultural land, especially in the Delta, due to urbanization. **As shown in Figure 1.16**, urban encroachment increased in the last 20 years with 201% of that of the year 2000.

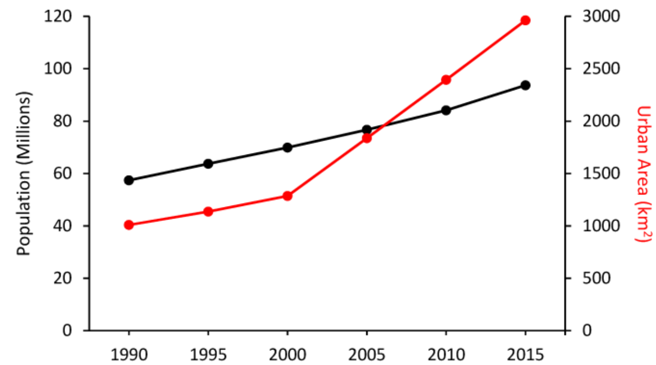


Figure 1.16: The rate of urban area enlargement against agricultural lands during the last 3 decades.

2. Climate Change

Fluctuations in temperature and rainfall patterns affect growing seasons and lead to reduced production. **As shown in Figure 1.17**, rising temperatures in the last decades increased the demand for cooling in factories, leading to higher energy costs. Climate change degrades soil quality, reducing agricultural yields. Changes in climate, such as floods or drought, lead to land degradation and the loss of produce that was grown on the land.

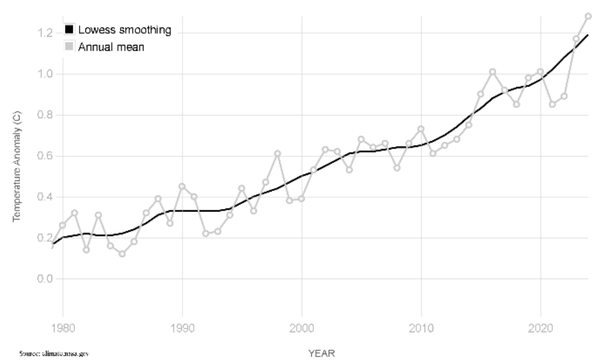


Figure 1.17: The changes in global surface temperature compared to the long-term average change from 1980 to 2020.

3. Lack of Agricultural Land

Egypt faces a major problem of land shortage in terms of cultivated and uncultivated lands. This has led to an increase in human pressure on environmental systems to a large extension of degraded lands due to the growth of the population which will need food, fuel, and some requirements, and an increase in demand for land for the population and infrastructure. This reduces the areas of agricultural land.

This demand is expected to rise to 50% and 30% by 2030. Deterioration of both types of soil because of the unstained use of fertilizers and pesticides. In addition, less agricultural prevents industrial base flourishment affecting food demands in the long term. Reduced agricultural land undermines developments in crop and grass productivity and may unevenly affect different sectors of industry.

Impacts

1. **Food Insecurity**

Egypt relies heavily on the agricultural and industrial sectors to obtain food. This affects the country's ability to secure food for its population, and this leads to Egypt's insecurity and food being exposed to danger. Food security affects health, growth, education, and economic productivity. Food insecurity leads to a group of problems such as stunting, obesity, and chronic diseases. It also leads to decreased economic productivity and increased poverty rates. Furthermore, Egypt has a moderate level of food insecurity, ranking 57 out of 125 countries accord toing Global Hunger index.

2. **Effects on Economy**

Poor agriculture and industry lead to the production of small quantities of the same available resources, and this reduces the overall productivity of the economy. It will reduce the ability to export products, and this will lead to a decline in revenues from foreign trade, which will subsequently affect Egypt's economy. Poor agricultural and industrial sectors increase unemployment rates and there will be a decline in labor demand in agriculture and industry. Poor agricultural and industrial sectors reduce sustainable economic growth and attract foreign investment, and this reduces the opportunities available to develop infrastructure and strengthen the economy in general.

Dealing with Population Growth and Its Consequences

Egypt is the third country in Africa in terms of population, following Nigeria and Ethiopia, and the first in the Middle East. Over the past decades, Egypt's population has been rising at a high rate compared to the global rate of approximately 0.9%, as stated by the World Bank. The population rose from 43.7 million in 1980 to 114.5 million in 2024. The annual growth rate is 1.57% in 2024, which is equivalent to 1.8 million individuals per year, whereas it was 2.44% in 1980, about 1 million. Although the rate is decreasing, the number added to the population is becoming greater. According to the World Population Prospects 2024 by the United Nations, it is estimated that Egypt's population will increase to 160 million by 2050, **as shown in Figure** 1.18.

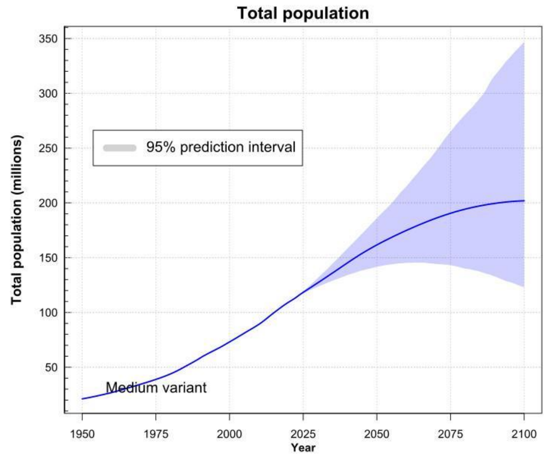


Figure 1.18: Predicted Population of Egypt till 2100.

Egypt's population distribution is extremely uneven, **as shown in Figure** 1.19. In 2023, approximately 43.1% of the total population was urban, often in crowded conditions, while the rural population was 56.9%. As of 2022, the total inhabited land in Egypt represented only 10.5% of its total land area, which equals 1,002,000 square kilometers. The actual population density, the total population divided by the inhabited area, is about 1,700 persons per square kilometer, whereas the expected density, the total population divided by the total area, is 115 p/km².

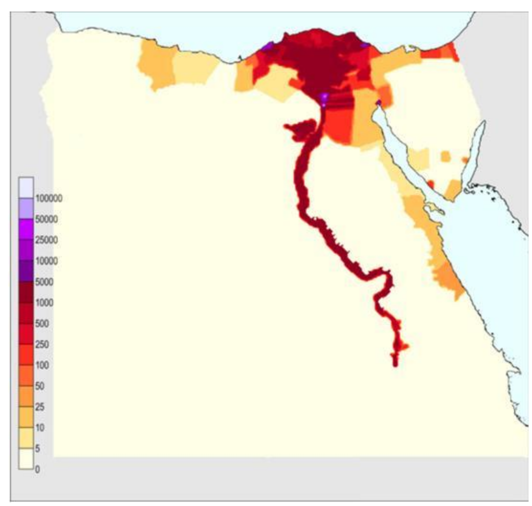


Figure 1.19: Map of population concentrated areas.

Cairo, Alexandria, and Giza are the main metropolitan areas in Egypt. Cairo is one of the most overcrowded cities in the world, where its population density is approximately 19,000 people per square kilometer. Population density exceeds 100,000 p/km² in some areas of Cairo and Alexandria. **As shown in Figure** 1.20**,** a study by Statista indicated that three Egyptian cities—specifically Tanta, El-Mahallah Al-Kubra, and Al-Mansura—are among the world's 12 most densely populated cities, with densities of 31,360, 25,979, and 23,962 inhabitants per square kilometer, respectively.

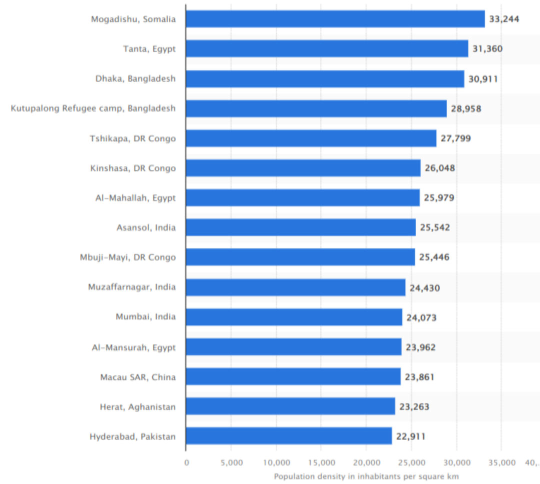


Figure 1.20: Population density in inhabitants per square km.

Egypt's resources are limited compared to its huge population. The environment and natural resources are strained by the fast population growth, which demands more production to meet the basic needs and employment of the people.

Causes

1. High Fertility Rate

The fertility rate is the average number of children born to a woman in her reproductive years. According to the United Nations Population Fund (UNFPA), Egypt's fertility rate is 2.8 children per woman as of 2023. This means that 2,448,253 children are born annually. Although this rate has been declining since 1980, **as shown in Figure** 1.21, it is still higher than the replacement-level fertility rate of 2.1 children per woman, which is the rate at which the population can maintain its size without migration. The huge number of annual newborns, in addition to increased life expectancy and a low rate of mortality, **as shown in Figure** 1.22**,** causes the population to grow rapidly. The high fertility level is due to some key factors, including traditions, education, and poverty. For example, rural and Upper Egypt is still dominated by ideas and beliefs that

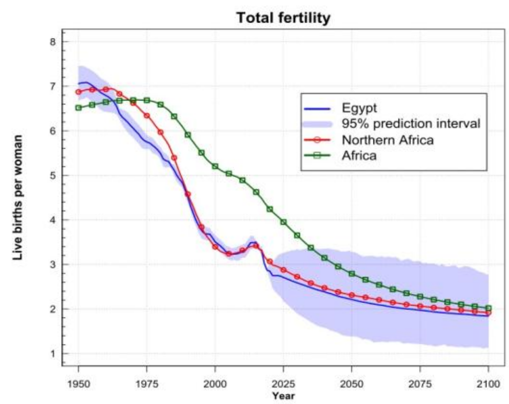


Figure 1.21: Total fertility.

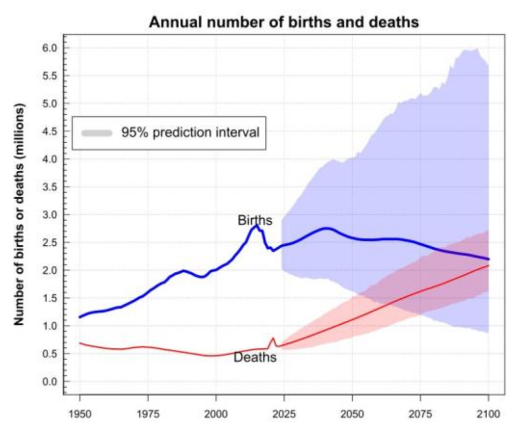


Figure 1.22: Number of births and deaths in Egypt.

emphasize the importance of families with an increasing number of children. These beliefs relate to the fact that large families can employ their children at an early age to help in agriculture, thus representing their economic power.

2. Forced Displacement and Migration

According to the United Nations High Commissioner for Refugees (UNHCR), forced displacement occurs when individuals and communities are forced or obliged to flee or leave their homes or places of habitual residence. This is in order to avoid the effects of events such as armed conflict, generalized violence, human rights abuses, natural or man-made disasters, or development projects. In 2022, the International Organization for Migration (IOM) estimated the total number of international migrants residing in Egypt to be 9 million migrants and refugees, accounting for about 9% of the total population. The outbreak of armed conflict in Sudan on April 15, 2023, led to the fleeing of large numbers of civilians to Egypt and neighboring countries. **As shown in Figure** 1.23, the total number of newly arrived refugees from Sudan is 460,000 as of January 31, 2024, according to UNHCR. Egypt also hosts 154,794 Syrian refugees and 114,230 from various nationalities.

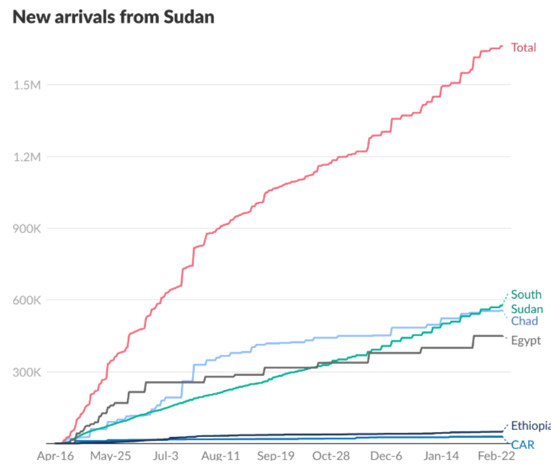


Figure 1.23: Number of new arrivals from Sudan.

3. Child Marriage

Cultures and traditions are key factors that affect the fertility rate, contributing to population increase. Child marriage refers to children who get married before the age of 18, as agreed in the International Convention on the Rights of the Child. Although the Egyptian Child Law, passed in 2008, prevents marriage under 18 years for both genders, child marriage is still being practiced in some regions of the country, especially in Upper Egypt. According to a 2017 census by the Central Agency for

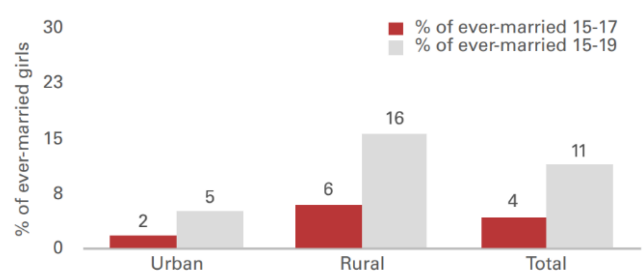


Figure 1.24: Number of married people in Egypt under 19 years.

Public Mobilization and Statistics (CAPMAS), nearly 4% of girls between the ages 15 to 17 and 11% of adolescent girls aged 15 to 19 years, are either currently married or were married before, **as shown in Figure** 1.24. Marriage at an early age is associated with a longer period of exposure to the possibility of pregnancy and thus higher fertility levels.

Impacts

4. Unemployment

The labor force is the number of people aged 15 to 60 who are working, not working, or searching for work. Unemployment refers specifically to those who are jobless or seeking a job within the labor force. The labor force of Egypt in 2022 was 32.6 million, with an unemployment rate of 7.2%, **as shown in Figure** 1.25**.** Such a high unemployment rate is due to rapid population growth accompanied by few available job opportunities. Economic deterioration has also affected the unemployment rate. Egypt's economy has faced a foreign exchange crisis and fiscal pressure due to global shocks. These challenges have forced Egyptian businesses to reduce employment. Thus, the number of job opportunities remains approximately constant while the population continues to increase.

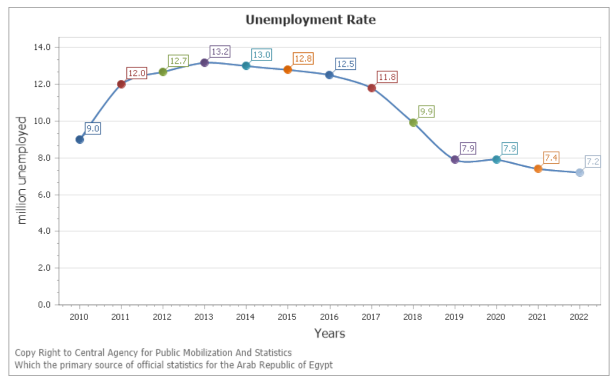


Figure 1.25: Unemployment rate in Egypt.

5. Poverty

In 2020, Egypt's national poverty line, the estimated minimum level of income needed to secure the necessities of life, stood at 10,300 Egyptian pounds. The projected poverty rate in 2022 was 27.3% of the total population, **as shown in Figure 1.26**. Population growth causes overpopulation, which increases demand over supply for consumable

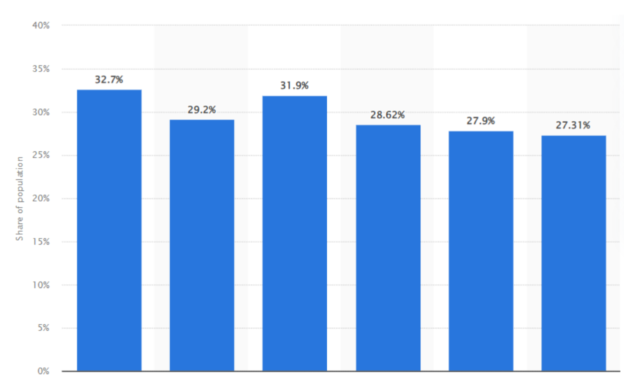


Figure 1.26: Poverty rate in Egypt.

products, forcing Egypt to import, which in turn raises prices. Rising prices, combined with unemployment, and decreasing salaries, push a significant percentage of Egyptians below the poverty line. For instance, the inflation rate in 2023 was 33.9%, according to CAPMAS, leading to high prices and increasing poverty.

6. **Slums**

Due to rapid population growth, people migrate from rural areas to urban cities in search of job opportunities and better living conditions. This has led to increased urban poverty, overcrowding, and thus the emergence of slum areas. According to the UN-Habitat, a slum is a contiguous settlement whose inhabitants are described as having inadequate housing and basic services. A slum household lacks either safe drinking water access to improved sanitation and other basic infrastructure, or both. It is also characterized by overcrowding, hazardous locations, and insecurity of tenure. Slums mainly exist around urban cities in Egypt and constitute about 38% of the total area of urban communities.

Problem to be Solved

Water Scarcity Impeding Land Reclamation and Agroforestry Efforts while Improper Wastewater Disposal Exacerbating Environmental Pollution Around the Rubiki Industrial Zone, Badr City, Egypt.

The increased water consumption due to the rising population in Egypt has led to more wastewater production causing environmental pollution. Moreover, water scarcity has been hindering the efforts of arid land reclamation. Thus, the need for managing and increasing the sources of clean water is essential for the development of Egypt. This can help increase the industrial and agricultural base of the country.

According to the World Bank, the agricultural and green land in Egypt accounts for only 4.1 percent of the total land area in 2022, while the majority of the country is deserts. The Food and Agriculture Organization of the United Nations (FAO) stated that the per capita share of agricultural land had been decreasing, reaching approximately 0.04 hectares in 2021.

After the 1952 revolution, the reclamation of desert lands to increase agricultural production was declared to be among the most important objectives of the Egyptian Government. These efforts have been hindered because of clean water scarcity, where, as stated by the United Nations, Egypt's annual per capita share of water declined to 570 m^3 in 2018 which is below the international standard of 1000 m^3.

Moreover, despite the country's efforts to build water treatment plants, most of the wastewater derived from agricultural and industrial applications is being improperly disposed of, leading to environmental pollution.

As the case in the Robbiki Industrial Zone, located in the Cairo-Suez district in northern Badr City, all industrial effluents are discharged into a series of stabilization ponds situated on the city's eastern outskirts. These ponds are currently experiencing diminished performance due to hydraulic overloading and inadequate filtration. Additional wastewater is discharged randomly into the desert due to the limited capacity of these stabilization ponds.

The effluent produced from the leather industry in the area mainly contains high concentrations of toxic substances that contribute to the increase in Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Chromium (Cr), and Nitrogen (N). This is of high concern due to its negative impact on the environment.

Depending on the above-mentioned data in addition to the large desert area surrounding the area, the chosen problem to be solved is water scarcity that impedes land reclamation and agroforestry efforts. At the same time, improper wastewater disposal exacerbates environmental pollution around the Rubiki Industrial Zone, Badr City, Egypt.

Positive Consequences

1. **Soil Amelioration**

Implementing effective wastewater treatment in the Robbiki Industrial Zone can significantly enhance soil quality through amelioration processes. Utilizing treated wastewater for irrigation can introduce essential nutrients and organic matter into the soil, improving its structure and fertility. Studies have demonstrated that adding organic amendments to saline soils increases nutrient availability and crop productivity. Therefore, the reuse of treated wastewater not only addresses water scarcity but also contributes to the reclamation of degraded soils, promoting sustainable agriculture.

2. **Promotion of Sustainable Industrial Practices**

Addressing improper wastewater disposal encourages industries in the Robbiki Industrial Zone to adopt sustainable practices. The Egyptian government has recognized the necessity for stringent regulations governing pollution control and waste management, establishing legal frameworks and institutional bodies dedicated to environmental protection. By complying with these regulations, industries can reduce their environmental footprint, enhance operational efficiency, and improve community relations. Implementing on-site wastewater treatment and recycling systems not only ensures regulatory compliance but also fosters a culture of sustainability, positioning industries as responsible and forward-thinking entities.

3. Increasing Green Spaces and Climate Change Mitigation

Utilizing treated wastewater for irrigation facilitates the expansion of green spaces through agroforestry and land reclamation projects. The "Future of Egypt" project aims to transform 16,800 square kilometers of desert into farmland by 2027, addressing food security and economic development. Expanding green areas enhances carbon sequestration, mitigates urban heat island effects, and improves air quality. Moreover, increased vegetation cover contributes to climate change mitigation by absorbing atmospheric carbon dioxide. Thus, integrating treated wastewater into irrigation practices supports environmental sustainability and aligns with national development goals.

Negative Consequences

1. Public Health Risks

Neglecting proper wastewater treatment poses significant public health risks. Improper waste handling and disposal can lead to the contamination of water sources with heavy metals and pathogens, increasing the incidence of waterborne diseases among local populations. In Egypt, life expectancy decreases by approximately 1.85 years due to air pollution, with 67,283 annual deaths attributed to related health issues. While this statistic primarily addresses air pollution, it underscores the broader health impacts of environmental contamination. Therefore, inadequate wastewater management can exacerbate public health challenges, straining healthcare systems and reducing quality of life.

2. Loss of Biodiversity

Improper disposal of industrial effluents can lead to the degradation of natural habitats, resulting in a loss of biodiversity. Pollutants such as heavy metals and chemicals can accumulate in ecosystems, adversely affecting flora and fauna. In the Nile Delta, water pollution has been linked to reduced fish varieties and a decline in aquatic life. The contamination of waterways disrupts food chains and diminishes biodiversity, which is crucial for ecosystem resilience and function. Protecting natural habitats through proper wastewater management is essential to preserve Egypt's rich biodiversity.

3. Deterioration of Ground Water Quality

Inadequate wastewater treatment can result in the infiltration of pollutants into groundwater reserves, compromising water quality. In Egypt, the Nile River, a primary water source, faces contamination from municipal and industrial waste, leading to the presence of heavy metals and pathogens in the water. This contamination poses risks to communities relying on groundwater for drinking and irrigation, potentially leading to health issues and reduced agricultural productivity. Ensuring effective wastewater treatment is vital to protect groundwater resources and maintain their safety for various uses.

Research

Topics Related to the Problem

Water Quality Index (WQI)

The quality of contaminated water, due to anthropogenic or natural factors, can be tested through changes in physical, chemical, or biological characteristics. By collecting samples and obtaining data at specific locations, the quality of water bodies can be expressed according to specific parameters depending on the changes that occurred. Whether a water source is suitable for human consumption can be described in terms of the Water Quality Index (WQI), reducing bulk information into a single value from 0 to 100. Since 1965, many water quality indices have been developed, differing in their calculation methods, selected parameters, and accuracy. The most recently developed index is the West Java Water Quality Index (WJWQI), carried out in 2017 and aimed to reduce the uncertainty of other indices. The thirteen selected water quality variables were: temperature, suspended solids, chemical oxygen demand (COD), dissolved oxygen (DO), nitrite, total phosphate, detergent, phenol, chloride, zinc (Zn), lead (Pb), mercury (Hg) and fecal coliforms. The WJWQI suggested 5 quality classes ranging from poor (5–25) to excellent (90–100), **as shown in Table 1**.

Table 1: WJWQI levels and status

WATER QUALITY INDEX LEVEL	WATER QUALITY STATUS
0 - 25	Very poor
26 - 49	Poor
50 - 70	Medium
71 - 89	Good
90 - 100	Excellent

Water Quality Parameters

Water quality parameters are indicators used to evaluate the suitability of water for various purposes. They include Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), fecal coliform, hardness, nitrogen, pH, and others. BOD measures the amount of oxygen consumed by the bacteria responsible for organic matter decomposition. It includes the amount of oxygen required for the oxidation of different chemicals, like ammonia and sulfide, in water. COD measures the amount of oxygen in a water sample available for oxidation by a strong chemical oxidant. DO, expressed in milligrams per liter (mg/L) or parts per million (ppm), is the mass of oxygen present per liter of water. Fecal coliform is a type of non-pathogenic bacteria found in animal intestines whose presence indicates possible contamination with pathogens. Water hardness depends on the concentration of calcium and magnesium, called temporary hardness. Permanent hardness depends on bicarbonate, carbonate, sulfates, chlorides, and other anions of mineral acids. Nitrogen occurs in natural waters in various forms including nitrate (NO3), nitrite (NO2), and ammonia (NH3). The nitrogen parameter indicates the available nitrogen content for uptake by plants. pH is an indicator for the acidity (below 7) and the basicity (more than 7) of water samples. A water sample of pH 7 is neutral. Each of these parameters has different ranges, on which the water quality is determined.

Environmental Impacts and Health Hazards Associated with Wastewater

Improper disposal of wastewater poses significant environmental and public health challenges. When untreated or inadequately treated wastewater is released into natural water bodies, it introduces pollutants such as heavy metals, chemicals, and pathogens, leading to the degradation of aquatic ecosystems. This contamination can result in the death of fish and other aquatic organisms, disrupting food chains and reducing biodiversity. Additionally, the presence of excessive nutrients in wastewater can cause eutrophication, leading to algal blooms that deplete oxygen levels and create "dead zones" uninhabitable for marine life. From a public health perspective, exposure to untreated wastewater increases the risk of diseases caused by viruses, bacteria, and parasites. Individuals in contact with contaminated water may experience gastrointestinal illnesses, skin infections, and other health issues. For instance, pathogens present in sewage can lead to diseases such as gastroenteritis, characterized by symptoms like diarrhea, abdominal pain, and vomiting. Moreover, workers handling human waste or sewage without proper protective measures are at heightened risk of infections and other health complications. Therefore, effective wastewater treatment and management are crucial to safeguarding environmental integrity and public health.

Topics Related to the Solution

Electric Coagulation

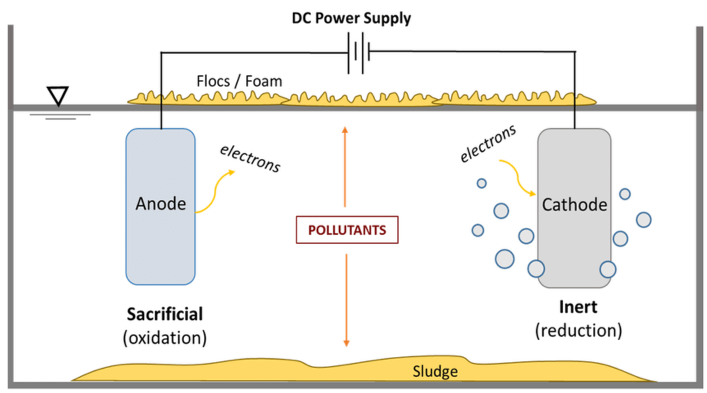


Figure 1.27: Electric Coagulation mechanism diagram.

Electric coagulation is a combination of physical and chemical processes widely used to remove different types of dirt by coagulating them. **As shown in Figure 1.27,** the process includes connecting a source of direct electric current (DC) with two rods immersed in the wastewater that is aimed at being treated. The positive side of the power source is connected to the anode in which the oxidation process occurs. Due to the oxidation process, the anode releases the iron of that metal into the water. These ions then react with water to form metal hydroxides. Due to the charge, these hydroxides stick to the dirt to form larger particles called flocs. These flocs can attract other dirt particles to form larger and larger particles. After a little time, these particles become heavier and settle down. In addition, due to the electric current, some of the water particles are decomposed into oxygen and hydrogen. These gases stick to other dirt particles and float on the water surface. Then, these pollutants become easy to remove by sedimentation or flotation.

A study proved that at optimal circumstances, a neutral pH, a 60-minute treatment duration, a voltage of 12V, and using aluminum electrodes, electric coagulation removed about 97.7% of the Chemical Oxygen Demand (COD). Another study proved its high efficiency in the reduction of heavy metals, pesticides, radio nuclides, and harmful microorganisms from wastewater. However, it has a disadvantage that the electrode at the anode is eroded over time and needs to be replaced periodically.

Biodegradation

Biodegradation is the process by which microorganisms such as bacteria, fungus, algae, protozoa, or green plants are introduced to wastewater and given time to either remove certain pollutants from the water medium or depolymerize them into harmless forms using intracellular and extracellular enzymes. The microorganisms use the carbon and energy obtained for growth and reproduction. Each species of microorganism has been found to be effective for certain types of pollutants, thus it is crucial to choose the right microorganism for each case.

Literature states that biodegradation is relatively sustainable and favorable in comparison to other types of wastewater filtration methods. Literature also states that, most often, the byproducts of biodegradation include carbon dioxide. This is a major negative point but can be solved by attempting to utilize such air in an application.

Biodegradation can be performed in both aerobic and anaerobic conditions. Although, the products of aerobic biodegradation often include water, CO_2, mineral salts, and biomass. On the other hand, the products of anaerobic biodegradation often include methane, carbon dioxide, and digestate. As anaerobic biodegradation produces 2 greenhouse gases rather than the 1 in aerobic biodegradation, it's likely that aerobic biodegradation is the better choice. Additionally, aerobic biodegradation is easier to perform and doesn't require sophisticated chambers/uncommon tools.

Biodegradation is also affected by many factors; both abiotic and biotic, **as shown in Figure 1.28**. Increases in temperature increase enzymatic activity. Contrastingly, enzymes denature at high temperatures, decreasing efficiency. High moisture can also speed up hydrolysis, a process done during biodegradation. UV irradiance cleaves $C-H$ bonds, increasing efficiency in some cases. Interestingly, for all the factors affecting biodegradation, none of them have universal patterns but are rather unique to each combination of microorganisms and pollutants. Thus, it's important to do specific tests for each use case to optimize it.

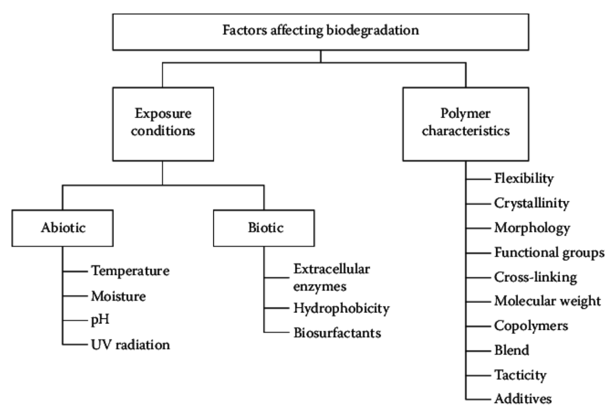


Figure 1.28: Factors affecting biodegradation.

Other Solutions Already Tried

El-Gabal El-Asfar Wastewater Treatment Plant.

Figure 1.29: El-Gabal El-Asfar Wastewater Treatment Plant.

El-Gabal El-Asfar Wastewater Treatment Plant, **shown in Figure 1.29,** is considered one of the largest wastewater treatment plants in the Middle East and Africa, with a total capacity of 2.5 million cubic meters per day as of February 2025. It is located in the northeast corner of Cairo, Egypt. It provides clean water to a huge number of Cairo's residents, estimated to be about 12 million people. The plant was built in multiple phases, with contributions from international organizations such as the Japan International Cooperation Agency (JICA) and the African Development Bank (AfDB), in addition to the Egyptian government funding. The first phase was completely built by 1998, with many expansions to come over the huge increase in the population number in Cairo alongside the increasing rate of water pollution.

Plans are made to expand the plant's capacity in the future to offer clean water to up to 17.5 million residents by 2040. The treated water is used in many fields such as drinking, agriculture, and other needs. In addition, the plant produces electricity as it creates biogas from the sludge treatment process. This makes the plant an eco-friendly solution to the problem of shortage of clean water sources in Egypt. In addition to treating sewage, the facility plays a crucial role in reducing pollution in the Nile River by ensuring that wastewater is properly processed before being released back into the environment.

Mechanism

El-Gabal El-Asfar consists of 5 main treatment stages, **as shown in Figure 1.30:**

The first stage is called the Preliminary Treatment. First, solid waste, such as plastics, fabrics, and others, is removed using large metal screens. Then, it moves to grit chambers, where heavier particles like sand and gravel settle at the bottom. This stage preserves the equipment used in the next stages from damage and ensures that only liquid effluent flows to the proceeding stages.

The next stage, Primary Treatment, includes the movement of the water into sediment tanks where solid waste slowly settles at the bottom, forming sludge. Lighter materials, such as oils, float on the surface and are removed. This phase helps remove about 60% of suspended solids from the wastewater before it moves on to the next stage.

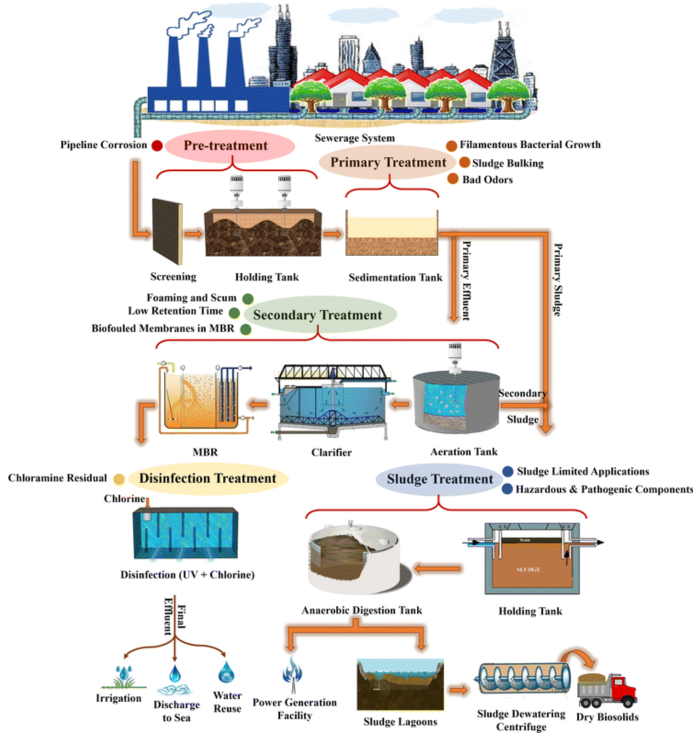


Figure 1.30: : Water treatment stages in El-Gabal El-Asfar.

Then, the water flows through the Secondary Treatment, where microorganisms are exposed to aeration tanks where the organic waste is broken down using oxygen. This is considered biological treatment, which significantly reduces the pollutants in the water. The mixture then moves into secondary clarifiers, where the remaining solids sink to the bottom, making the water much cleaner and safer for reuse.

The water then moves to the Tertiary Treatment. In this stage, the water passes through a disinfection process by exposing it to chlorination or ultraviolet (UV) light. This stage aims to kill bacteria and other pathogens, ensuring that the treated water meets strict safety standards before being discharged into natural water bodies or repurposed for agricultural and industrial use.

The last stage is the Sludge Treatment in which the collected sludge from previous stages is directed to large anaerobic digesters, where bacteria break down the organic material in an environment free of oxygen. This process generates biogas, primarily methane, which is then used to produce electricity for the plant. The remaining sludge is further treated, dried, and converted into fertilizer for agricultural use or disposed of safely.

Points of Strength

1. **High Treatment Capacity**

With a daily capacity of 2.5 million cubic meters, El-Gabal El-Asfar plays a critical role in Cairo's wastewater management. The plant processes about 91% of the region's wastewater, preventing contamination of natural water sources and reducing the spread of diseases. This large capacity also ensures the city can handle increased sewage loads as the population continues to grow.

2. **Energy Recovery through Biogas Production**

The plant produces around 65,000 cubic meters of biogas daily, which is converted into approximately 65 megawatts of electricity. This accounts for nearly 60% of the plant's energy needs, significantly cutting down on operational costs. Additionally, by using biogas instead of fossil fuels, the plant reduces greenhouse gas emissions by nearly 200,000 metric tons per year, contributing to Egypt's commitment to environmental sustainability.

3. **Environmental Protection**

The facility prevents untreated wastewater from polluting the Nile River, ensuring the preservation of aquatic ecosystems. The treated water is reused to irrigate over 150,000 acres of farmland, reducing the demand for fresh Nile water and supporting local agriculture. Additionally, the proper treatment of sewage reduces harmful bacteria and contaminants, protecting public health and improving overall sanitation conditions in Cairo.

Points of Weakness

1. **High Operational Costs**

Running the plant requires an annual budget of approximately 1.2 billion Egyptian pounds for maintenance, energy consumption, and labor. Advanced filtration and sludge management technologies demand continuous investment, making long-term sustainability financial challenging. The reliance on government funding and external financial aid highlights the need for more cost-effective solutions in the future.

2. **Infrastructure Challenges**

Cairo's rapidly growing population means the wastewater system must continuously expand to prevent overloading. By 2030, the plant will need an additional 20% increase in capacity to keep up with demand. This requires substantial financial investment, land availability for expansion, and advanced technology to improve efficiency. Without these upgrades, untreated wastewater could overflow into natural water bodies, leading to environmental and public health risks.

3. **Sludge Disposal Issues**

The facility produces around 800 tons of sludge every day. While some of it is converted into fertilizer, managing excess remains a significant challenge. Improper disposal can lead to soil and water contamination, requiring ongoing investment in sludge processing and environmentally friendly disposal methods. The plant is working on increasing sludge processing efficiency by 30% within the next decade to address these concerns.

New Cairo Wastewater Treatment Plant

Figure 1.31: The New Cairo Wastewater Treatment Plant.

The New Cairo Wastewater Treatment Plant, **shown in Figure 1.31,** was built in New Cairo City, an extension of Greater Cairo. The Egyptian Ministry of Housing, Utilities & Urban Development (MHUUD) initiated the project, and it was awarded in 2009 to Orasqualia, a joint venture between Orascom Construction Industries and Aqualia. This consortium was responsible for the design, construction, financing, operation, and maintenance of the facility under a 20-year concession agreement. The construction of the plant began in February 2010, and it was operated in March 2012. The total cost for the project was approximately 472 million dollars. Funding was secured through a debt package of 103 million dollars over a 15-year tenure. Four Egyptian banks provided this funding which are National Société Générale Bank (NSGB), Commercial International Bank (CIB), Arab African International Bank (AAIB), and Ahli United Bank.

New Cairo City, with a population of 550,000 in 2009, is predicted to increase to 3 million by 2029. The plant was constructed to fill the demand for clean water in this expanding population city and its surrounding areas. The plant, initially, was designed with a capacity of 250,000 cubic meters per day (m^3/Day), which is enough to provide up to 1 million residents with pure water. Plans are made to expand the plant's capacity up to 500,000 m^3/Day to accommodate future population growth and increased wastewater generation. The New Cairo Wastewater Treatment Plant serves adjacent cities other than New Cairo, for example, Madinaty and El Mostakbal cities.

Mechanism

The New Cairo Wastewater Treatment Plant contains many stages to filter different types of pollutants. These stages are **shown in Figure 1.32** and are explained below.

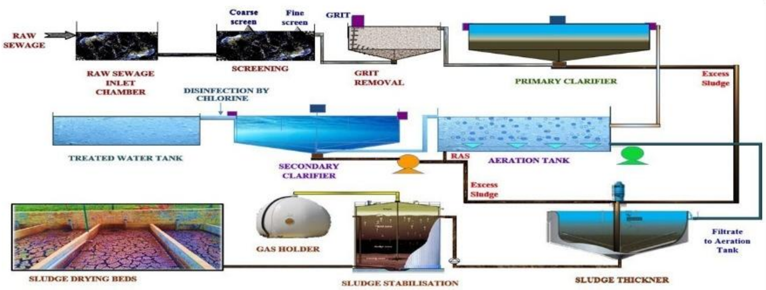


Figure 1.32: Wastewater way in New Cairo WwTP.

The first stage is called Inlet Works and Pre-Treatment, where the Wastewater is conveyed to the plant through reinforced concrete pipes measuring 2,200mm in diameter. Then, four automatic screens, each 1.5 meters wide, remove coarse and fine solids to protect downstream equipment. Before the water enters the next stage, four circular units, each with a volume of 11,679 cubic meters, facilitate the settling and removal of sand and heavy particles to ensure the safety of equipment used in the next stages.

Then, in the Primary Stage, wastewater flows into gravity-based sedimentation tanks where suspended solids settle as sludge, reducing the organic load. Then, by biological treatment, the plant utilizes six biological reactors divided into anoxic zones (2,970 cubic meters each) and aerobic zones (11,610 cubic meters each). In the anoxic zones, microorganisms degrade pollutants without oxygen, while in the aerobic zones, aeration supports further decomposition of organic matter. Furthermore, fourteen horizontal centrifugal pumps ensure optimal microbial activity.

During the Secondary Treatment, treated water enters six secondary settling tanks where the remaining solids are separated, resulting in clarified effluent. This stage is followed by the Tertiary Stage, where eleven textile mesh filters, each capable of filtering 1,374.37 cubic meters per hour, perform fine filtration to remove the remaining particulates.

The last stage is the Sludge Treatment, where the collected sludge is processed in digesters where bacteria decompose organic material, producing methane-rich biogas. The generated biogas covers over 50% of the plant's energy needs, enhancing sustainability. The remaining sludge is treated and converted into organic fertilizer, promoting resource recovery.

Points of Strength

1. **High Treatment Capacity and Future Expansion**

Initially, the plant was built to treat 250,000 cubic meters of wastewater a day, which could help 1 million residents. However, due to the rapid urban expansion of New Cairo and surrounding cities such as Madinaty and El Mostakbal, the plant is expected to double its capacity to 500,000 cubic meters per day by 2029. This expansion will help accommodate the projected population growth of New Cairo, which is estimated to reach 3 million residents by 2029.

2. **Energy Efficiency and Renewable Biogas Production**

One of the most important strengths of the plant is its ability to produce renewable energy and maintain a sustainable environment. Through its anaerobic sludge digestion process, the plant produces methane-rich biogas, which supplies more than 50% of its total energy requirements. This helps reduce dependence on non-sustainable electricity sources, which in turn decreases operational costs and carbon emissions. This supports national sustainability goals and contributes to reducing greenhouse gas emissions by thousands of tons per year. This initiative helps align with Egypt's Vision 2030 strategy for environmental sustainability.

3. **Support for Agriculture and Industrial Reuse**

The treated water from the New Cairo WWTP is not wasted; it is repurposed to benefit agriculture and industrial applications. The plant produces over 1,374 cubic meters per hour of highly filtered water, which is reused for irrigation in agricultural lands and parks. This reduces the dependency on fresh Nile water, ensuring more sustainable water use in a country where over 90% of freshwater resources are used for agriculture. Additionally, the facility converts organic sludge into fertilizer, supporting local farmers with nutrient-rich soil additives that enhance agricultural productivity. The availability of treated wastewater for irrigation also reduces the costs for farmers, providing an economic advantage.

Points of Weakness

1. **High Operational and Maintenance Costs**

The initial cost of the plant was about 472 million dollars, which is considered a high cost. In addition, it requires millions of dollars annually for operation. Energy consumption, infrastructure maintenance, and labor costs contribute to the high expenses. Although the plant produces about 50% of its uses of energy, the other 50% is relatively high in cost and thus requires external funding.

2. **Challenges in Sludge Management and Disposal**

The plant produces a significant amount of solid sludge daily, requiring extensive treatment and disposal solutions. While some sludge is converted into organic fertilizer, a large portion still needs further processing or safe disposal. Improper sludge management can lead to soil and water contamination, negatively affecting agriculture and local communities. The existing treatment facilities must continually be upgraded to handle the increasing sludge output efficiently.

3. **Growing Population Demands**

The demand for wastewater treatment is expected to rise significantly as New Cairo’s population expands to 3 million by 2029. Despite planned capacity expansions, there is a risk that the plant may not be enough for future demand. If the plant fails to expand on time, untreated wastewater may be discharged into rivers or underground water sources, which will cause public health risks.

Bahr El-Baqar Wastewater Treatment Plant

Figure 1.33: Bahr El-Baqar Wastewater Treatment Plant

A part of the Sinai development program, Bahr El-Baqar, **shown in Figure 1.33**, is one of the largest wastewater treatment plants in the world, located 10 km south of Port Said tunnels in Sinai, 17 km away from Al-Qantara city. The plant is a well-known national project aiming for a sustainable, clean water source for irrigation by recycling agricultural, industrial, and sewage wastewater. With a total area of 155 Feddans (650,000 m^2), the plant treatment capacity is the plant through four units of water treatment with a capacity of 1.4 million cubic meters per day. The main routes of wastewater treatment include water intake pumping buildings, mixing basins, sedimentation, and ozone and chloride tanks. The wastewater treatment process produces up to two billion cubic meters per year of clean water, producing competent amounts of water for irrigation with high-quality standards of purified water. The wastewater treatment plant consists of four identical units for physical and chemical tertiary treatment phases in addition to 2 units for sludge treatment.

Mechanism

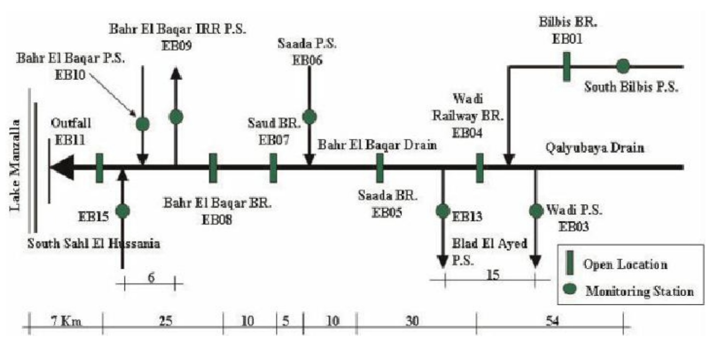


Figure 1.34: Schematic diagram for Bahr El-Baqar drain.

The infrastructure of the Bahr El-Baqar plant **as shown in Figure 1.34**, consists of 2 intake canals and outlet canals, water treatment lines (physical and chemical treatment phases), and sludge treatment lines. Each water treatment unit amounts to 1.4 million cubic meters per day. The first stage, the pretreatment phase, pumps water, with a velocity of 4 m^3 per second, through the coarse and fine refineries to remove plankton of different sizes, after which water will flow to the next phases. By adding some substances to adjust pH levels, the formation of flocculants occurs beneath the sedimentation basins. Then, water continues through routes and pumps to triple disc filters, where 120 filters are used for more efficient filtration. Post-water treatment includes sterilizing water by ozone or chlorine injection. The filtering surface amounts to 32 800 square meters of fine polyester membrane and a filter size of 10 microns to achieve the highest quality and standards of purified irrigation water. The post-treatment phase consists of water sterilization by using ozone or chlorine injections to aid the disinfection of water before the last purification contact tanks to decrease water odors. **Figure 1.35** shows the wastewater treatment phases in the Bahr El-Baqar plant.

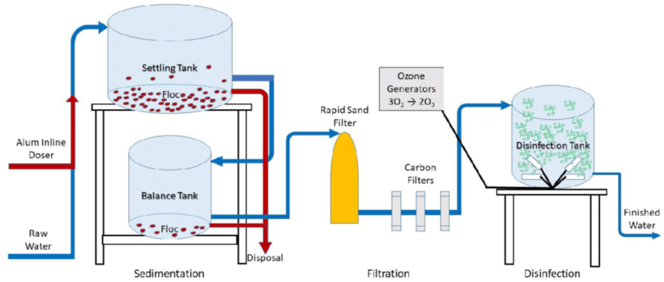


Figure 1.35: The wastewater treatment phases including disinfection.

Points of Strength

1. **Huge Capacity**

One of the biggest wastewater treatment plants in Egypt, the plant purifies a competent amount of water for irrigation. 1.25 million cubic meters per day of treated water passes through 4 treatment phases as wastewater is collected from the main drain before being available for farmers. The plant copes with the problem of lack of water and irrigation in Egypt. The plant provides water for up to 168 thousand hectares of agricultural land in Egypt. Water passes through 120 triple disc filters with a capacity of 1992 cubic meters per hour.

2. **High Treatment Quality**

Bahr El-Baqar plant has two main lines: wastewater and sludge line, ensuring high-quality treatment. Each line consists of 4 identical units for physical and chemical tertiary treatment processors. The wastewater treatment line takes water from two canals and rapid, slow mixing basins in addition to filters consisting of a 32,800-meter square 10-micron-size polyester membrane as the filtering surface. With a drying level of 24%, the sludge drying units have a capacity of 490 thousand tons/year.

Points of Weakness

1. **Management Complexity**

Bahr El-Baqar is the largest of its kind in the world. However, its scale and complexity lead to high operational and maintenance costs. High costs arise from some factors, such as labor, energy consumption, and chemical usage during treatment phases. With rising global temperatures, Egypt faces rapid expansion in water demand, leading to more stress on the plant to achieve the quality required. Keeping the plant under optimal conditions to prevent system overload is one of the maintenance challenges. System overload that is more than its capacity, 1.4 million cubic meters per day, leads to a decline in efficiency and partially untreated discharged water. Power outages affect clean water discharge as Egypt faced some problems in power that affected some facilities, including wastewater plants.

2. **Sludge waste pollution:**

Thousand tons of sludge waste and byproducts produced by the Bahr El-Baqar plant, 490 thousand tons per year, should be maintained by efficient disposal. **As shown in Figure 1.36**, sludge samples contain heavy metals and chemicals that cause pollution. Drying technology used to minimize odors and pollution from sludge is not sufficient to maintain its hazards, as large-scale sludge treatment has risks during extreme weather conditions. Before the construction of the plant, the Bahr El-Baqar drainage canal was a source of pollutants due to wastewater discharge that was not managed properly until the year 2021, so dealing with sludge waste and waterbodies threatened the environment.

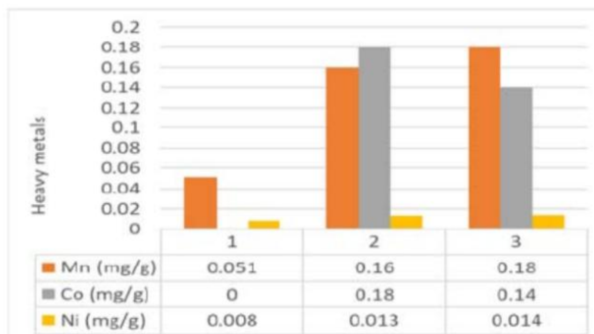


Figure 1.36: The heavy metals concentrations in sludge samples produced from the plant

3. **High Material and Maintenance Costs**

Wastewater treatment plants require additional chemicals during phases of treatment to check the purification and treatment of water for irrigation. The physical and chemical treatment phases, for example, acquire coagulants for sedimentation, disinfectants like chlorine and ozone, and pH adjusters to obtain and maintain optimal conditions. With more than 44 million EGP of substantial investment, treatment unit capacities are about 1.4 million cubic meters per day. Over time, these chemicals decrease and are replaced, so procuring and handling these chemicals add more load to the operational budget.

Abu Rawash wastewater treatment plant

Figure 1.37: The Abu Rawash Water Treatment Plant (ARWWTP).

Supported by the African Development Bank, the Abu Rawash Water Treatment Plant (ARWWTP), **shown in Figure 1.37**, is the second largest wastewater treatment plant in Egypt and the top 10 in Africa. The plant is 8 km northwest of the pyramids near the western bank of the Nile, Giza. The whole project aims to provide equitable and sustainable water sources through an efficient and strategic framework. Furthermore, the treatment plant increased agricultural production by providing treated water and improved the quality of life for the population. As a partner for half a century, the African Development Bank supported the construction of the treatment plant, and now the treated water is 10 times cleaner than before. Serving 6 million people in greater Cairo, the Amount of water treated is expected to reach 2 million cubic meters of wastewater per day instead of 1.6 million cubic meters in the next few years. The plant was designed to treat an average discharge of wastewater up to 1.6 million cubic meters per day, the treated water is then discharged into Al-Rahawi drain.

Mechanism

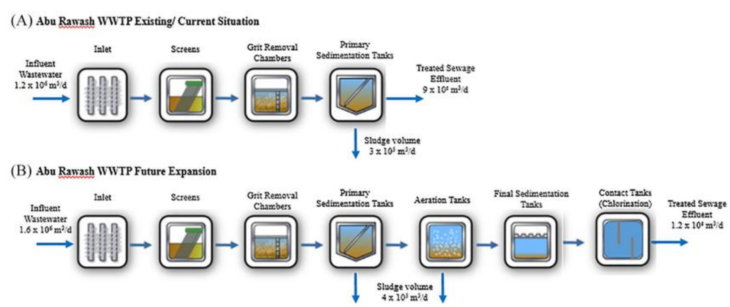


Figure 1.39: Wastewater Treatment Process for (A) Abu Rawash WWTP Existing/Current Situation. (B) Abu Rawash WWTP Future Expansion. (WWTP is wastewater treatment plant).

The plant follows a multi-stage treatment mechanism with 5 main phases: Pretreatment, Sedimentation, Secondary treatment, Disinfection, and Sludge Treatment. Primary treatment at first includes screening and basic filtration using polyesters for large debris and solid waste removal. **As shown in Figure 1.38**, the grit chambers allow sand and heavy particles to settle, preventing any damage downstream. The next phase is the primary sedimentation tanks, where sludge formation takes place. After this phase, 40% - 50% of suspended solids are removed from the wastewater stream. Wet Sludge wastes from primary and secondary treatment undergo another process to dry the sludge. Abu Rawash plant has the potential to produce 1.2 million cubic meters per day. Post-water treatment includes sterilizing water by ozone or chlorine injection, as chlorine, for example, kills 99% of bacteria, is fed into the water to kill pathogenic bacteria, reducing odors. After disinfection using chlorine, clean water is discharged into Rosetta branch through routes and pumps. **Figure 1.39 shows** the wastewater treatment process for Abu Rawash WWTP, the Current Situation, and Abu Rawash WWTP's Future Expansion.

Points of Strength

1. **Advanced Treatment Technology:**

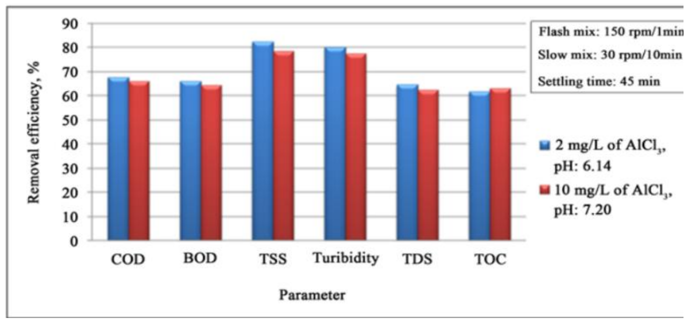


Figure 1.40: The removal effeciency for different paramters in Abu Rawash WWTP.

Wastewater proceeds through many phases till the discharge at the Rosetta branch. The initial BOD concentration was 169 mg/L. Application of 2.0 mg/L of aluminum chloride at pH 6.14 reduced the BOD concentration at the effluent from 169.0 mg/L to 57.60 mg/L. The maximum removal efficiency, **as shown in Figure 1.38**, of BOD was 66.0%, whereas it was limited to 40.0% for the blank sample. For the same dose, the COD, TSS, turbidity, TDS, and TOC reached maximum removal efficiencies of 67.60%, 82.20%, 80.10%, 64.60%, and 61.80%, respectively.

2. **Huge Capacity and Coverage**

1.90 million m^3 of drainage water is discharged daily from Abu Rawash plant considered the second largest wastewater treatments plant in Egypt. The plant purifies large amounts of water for irrigation and uses activated sludge treatment method. The last improvements in the plant capacity allow the plant to control an average flow of 800 thousand cubic meters per day at least. However, the excess sewage is discharged directly to the El-Rahawy drain without any treatment. The effluent from the plant passes through Barakat drain, the Al-Ramal drain, the Al-Labene drain, the Al-Mariotya drain, and the El-Rahawy drain before being available for farmers. Additionally, Abu Rawash plant copes with the problem of lack of water and irrigation in Egypt. The plant provides water for up to 133 hectares of agricultural lands in Egypt.

Points of Weakness

1. **Air Pollution and Byproducts**

Abu Rawash uses chemicals for wastewater treatment and contributes to air pollution as wastewater plants are a source of aerosols posing health risks. For example, the Abu Rawash plant emits various types of pollutants into the atmosphere such as CO, NO2, SO2, and NH3. **As shown in Figure 1.41**, the concentration of PM1 is high around the treatment basins of the plant. Furthermore, according to some research and studies, the average concentrations of biological oxygen demand (BOD), Chemical oxygen demand (*COD)*, total suspended solids (TSS), total dissolved solids (TDS), Dissolved Oxygen (DO) drain were 270, 146.7, 159.25, 720, 9.2, and 1.45 mg/L respectively. Byproducts such as sludge and high heavy metals concentrations pollute the drainage system if not dealt with properly.

Figure 1.41: The concentration of PM1 in Abu Rawas WWTP.

2. **Health Risks**

Although Overloaded sewage is discharged directly to the El-Rahawy drain without appropriate treatment rising water pollution in the drains and the Rosetta branch. **As shown in Figure 1.42**, pollutants like H_2S and VOCs are high. Hazards were evaluated as a hazard

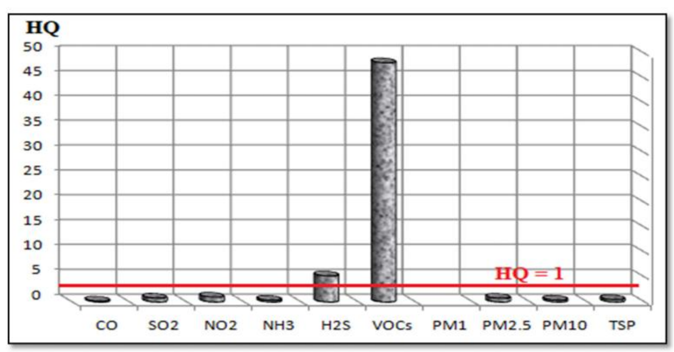


Figure 1.42: HQ of air pollutants detected in Abu-Rawash WWTP.

quotient (in terms of HQ, dimensionless). So, there are chronic adverse health effects caused by exposure to H2S and VOC. Over a long period, pollutants will affect the public health around the plant area, causing adverse health impacts such as cardiovascular and lung diseases as well as premature mortality.

3. **High Cost**

Abu Rawash's total investment of 320 million dollars that was allocated to improve its capacity and treatment technologies. During construction, changing the effluent path of the Abu-Rawash plant to the desert cost about 400 million EGP for constructing a canal 32 kilometers long. The problem lies in the operational and energy consumption costs that support the plant to serve more than 8 million people with clean water. **As shown in Figure 1.43**, the cost for wastewater treatment per cubic meter was found to be 0.075, 0.04, and 0.1EGP, respectively. The quicklime cost, ferric chloride, and alum ($AlCl_3$) are used to treat one cubic meter of wastewater and reach the required treatment efficiency. However, using such chemicals places more costs on the operational system of the plant. The required solution to this problem is to use cost-effective chemicals rather than the other proposed ones.

Term	pH: 6.14	pH: 7.20
$AlCl_3$ dose, mg/L	2.0	10.0
$AlCl_3$ dose, ton/m^3	0.000002	0.00001
$AlCl_3$ cost, EGP/ton	1300	1300
$AlCl_3$ cost, EGP/m^3	0.0026	0.013
Carbon dioxide cost, EGP/m^3	0.0008	N/A
Total cost, EGP/m^3	0.0034	0.013
Total cost, dollar/m^3	0.000485	0.00185

Figure 1.43: The treatment cost estimation at different pH values.

2. Chapter 2: Generating and Defending a Solution

Solution Requirements

Cost Effectiveness

The chosen solution should be cost-effective, meaning it generates savings or revenue that exceeds its initial investment. This can be achieved by utilizing affordable and efficient materials.

Eco-friendliness

The solution must minimize negative environmental impacts during both construction and operation. The construction methods and operational mechanisms should not emit harmful substances or pollutants. Additionally, the materials used should be natural, recycled, or recyclable.

Availability of Materials

The materials and methods employed in the solution should be widely accessible to ensure applicability in various regions around the world. This will facilitate addressing the prescribed problem in multiple countries, not just in Egypt.

Safety

The solution should be user-friendly and safe for all users. It must not emit any toxic gases, and measures should be in place to prevent leaks or explosions. Furthermore, extreme temperatures associated with the solution should not pose a risk to users.

Sustainability

The solution should be designed for long-term operation with minimal maintenance requirements, thereby reducing overall costs. It should also maintain its efficiency regardless of the varied weather and environmental conditions.

Scalability

The solution should be scalable, allowing for easy expansion and adaptation to meet growing demand. Modular design enables components to be added or removed as needed. It should integrate with existing infrastructure and facilitate replication in various regions, optimizing resource use and minimizing costs.

Design Requirements

The permissible thresholds for water quality parameters have been established following **the Egyptian Code for the Reuse of Treated Wastewater for Agricultural Purposes (ECP 501-2015).** These parameters are as follows:

- **Salinity (Total Dissolved Solids - TDS):** The maximum allowable concentration is 450 ppm, whereas wastewater intended for treatment should have a minimum salinity of 1000 ppm.
- **pH Level:** The pH of treated water must fall within the range of 6.5 to 8.5 to ensure its suitability for agricultural use.
- **Turbidity (Cr):** The level of turbidity in treated wastewater should not exceed **50 NTU** to prevent toxicity and ensure environmental and agricultural safety.

Selection of Solution

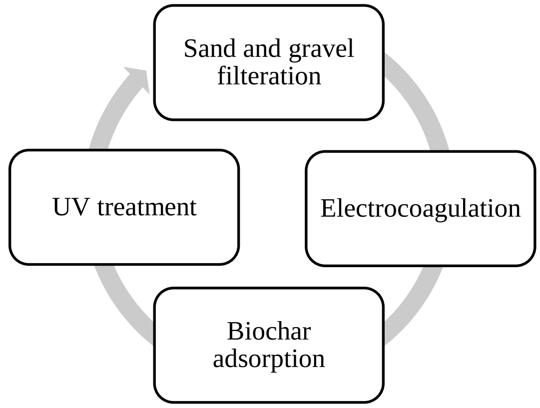


Figure 2.1: Wastewater treatment stages in the selected solution.

The proposed solution utilizes a combination of physical, chemical, and biological methods to treat tannery wastewater to reach the thresholds pre-defined in the design requirements. These methods are in the following order: sand and gravel biofiltration, electrocoagulation, biochar adsorption, and ultraviolet (UV) disinfection, **as shown in Figure 2.1**. Wastewater will cycle in these stages until the aforementioned thresholds are reached. Treated water will be used in the irrigation of specific plants suitable for land reclamation.

The first stage of the wastewater treatment process, sand and gravel screening, involves multiple layers of coarse gravel and fine sand. This system serves primarily to remove suspended solids and turbidity. The coarse gravel acts as a pre-filter, removing larger particles, while the fine sand traps smaller suspended solids. The biofilm that forms on the sand layer also contributes to the breakdown of organic matter, reducing the Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). By the end of this stage, a significant reduction in BOD and COD is achieved, with removal efficiencies that help bring the wastewater closer to the required limits, specifically keeping the BOD $\leq$ 80 ppm and COD $\leq$ 100 ppm.

In the electrocoagulation stage, electrodes (preferably made from recycled iron or aluminium) are used to create an electrical charge that destabilizes and aggregates contaminants in the wastewater, allowing them to form flocs that can be easily removed. This process effectively removes heavy metals, including chromium (Cr), and other toxic substances. It also reduces suspended solids and helps in further lowering the BOD and COD levels. Electrocoagulation is especially efficient in treating industrial wastewater, such as tannery effluent, by removing pollutants that biochar or filtration may not fully address. This stage ensures that the chromium concentration is reduced to below the required 0.1 ppm level, meeting the design requirement for safe agricultural use.

The next treatment stage is biochar adsorption, where biochar made from agricultural waste (e.g., rice husks, coconut shells) is used to adsorb organic pollutants, including dyes, oils, and other harmful chemicals. Biochar has a high surface area, which enhances its ability to adsorb contaminants. This process not only helps to remove dyes from the wastewater but also reduces BOD and COD further. Additionally, biochar can adsorb certain heavy metals, contributing to a reduction in chromium (Cr) concentration, which should be kept below 0.1 ppm to ensure environmental and agricultural safety. Biochar's natural composition ensures the process is sustainable and requires minimal energy input, thus aligning with the project’s focus on natural and recycled materials.

The last stage, UV disinfection, utilizes ultraviolet light to disinfect the treated water by deactivating harmful pathogens such as bacteria, viruses, and protozoa. UV light penetrates the microorganisms' cellular structure, damaging their DNA and rendering them incapable of reproduction, which effectively sterilizes the water. This stage is essential for ensuring that the treated water is safe for irrigation and prevents the spread of waterborne diseases. UV disinfection is an environmentally friendly alternative to chemical disinfection, as it does not leave any harmful byproducts, such as chlorine disinfection byproducts (THMs), which can negatively impact plant growth and soil health. The UV disinfection step ensures the treated wastewater meets the required health and safety standards, making it suitable for use in irrigation without introducing harmful pathogens to the environment.

Selection of Prototype

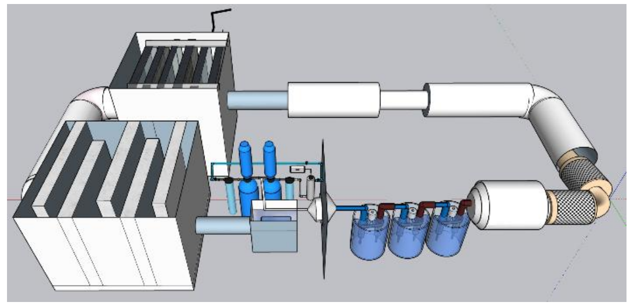


Figure 2.2: The 3D model of the prototype.

The proposed solution involves the development of a multi-stage water filter, as shown in the 3D model **in Figure 2.2**. Such stages will be in different containers, with the water flowing through them using pumps at fixed flow rates. Each container will be optimized for the different methods used.

As water enters the system, it'll first be met by a screen consisting of gravel and sand in the first container. This will remove any large particles before the other, more sophisticated, stages are initiated.

The second stage, which will house the electrocoagulation process, will contain the electrocoagulation process. Previous research has found that the usage of electrodes made from iron is most optimal for the removal of chromium, which will be the goal of this stage.

The third container consists of biochar. Although this can remove many pollutants, it'll mainly be used to remove the dye content of the tannery wastewater. The water will then be passed through UV light to remove any bacteria or other organic matter.

A final container will be utilized for the sensors. This container will contain TDS, pH, and heavy metal sensors. Each of those sensors will feed data to an Arduino system, which will check to see if certain threshold values for all the different parameters have been reached. Upon reaching them, the pump will be turned off automatically, and final readings will be taken after the water settles down completely.

3. Chapter 3: Constructing and Testing a Prototype

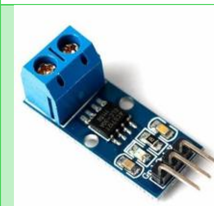
Materials and Methods

Table 2: The materials used in the prototype construction.

Item	Quantity	Description	Cost	Source	Picture
plastic buckets	3 buckets	Used as containers for the main container, Electrocoagulation, and the sand-gravel filter.	Donated	–	
water pumps	6 pumps	Used to pump water from each container to its following one.	330 EGP	Electronics shop.	
Silicon tubes	3 meters	Used to connect the containers together and let the water pass through them	90 EGP	Electronics shop	
Crocodile Wires	8 Wires	Used to connect the electrodes of the electrocoagulation stage	64 EGP	Electronics shop	
UV lamp	1 lamp	Used in the sterilization stage	800 EGP	Electronics shop	
Activated carbon	0.25 Kg	Used in the adsorption process	----	Recycled	
Sand	0.3 Kg	Used in the sand filter	----	Recycled	
Gravel	0.3 Kg	Used in the sand filter stage	----	Recycled	

Plastic bottles	2 bottles	Used as containers in UV and activated carbon stages	----	Recycled	
Arduino UNO	1 board	An Arduino UNO was utilized as the central control unit for the system of sensors and pumps.	Owned	–	
Breadboard	1 board	A breadboard was employed to assemble the electric circuit.	Owned	–	
Jumpers	50 jumpers	Jumpers were used to connect the different components of the circuit.	36 EGP	Electronics shop	
Glue sticks	5 sticks	Glue sticks were utilized to adhere various components of the prototype together.	50 EGP	Stationery	
Aluminum sheets	8 sheets	Used as electrodes in the electrocoagulation	60 EGP	smith	
Stainless steel mesh	15-cm-diameter circle	A steel mesh was employed to support the layers of activated carbon, sand, and gravel within the filter.	17.5 EGP	Paint shop	

Relay module	8-channel relay	Used to control opening and closing the pumps.	250 EGP	Electronics Shop	
Adaptor	6-Volt 2-Ampere Adaptor	Used to power the pumps	250 EGP	Electronics Shop	
Power supply	24-Volt 10-Ampere power supply	Used to power the electrocoagulation	400 EGP	Electronics Shop	
Electric Wires	8 meters of 1mm-diameter Wires	Used to connect the power supply to the Electrocoagulation	120	Electrician	
pH sensor	1 sensor	Used to detect the pH level in the water	1700 EGP	Electronics Shop	
Turbidity sensor	1 sensor	Used to detect the level of the total suspended solids in the water	650 EGP	Electronics Shop	
TDS sensor	1 sensor	Used to detect the level of the total dissolved solids in the water	750 EGP	Electronics Shop	
Temperature sensor	1 sensor	Used to detect the temperature of the water which is required for the TDS sensor	60 EGP	Electronics Shop	

Water flow sensor	1 sensor	Used to detect the water flow rate to know when each cycle comes to an end	250 EGP	Electronics Shop	
Current intensity sensor	1 sensor	Used to detect the current used in the system	110 EGP	Electronics Shop	
Voltage sensor	1 sensor	Used to detect the potential difference across the system to detect the power used	100 EGP	Electronics Shop	

Methods

Prototype Construction

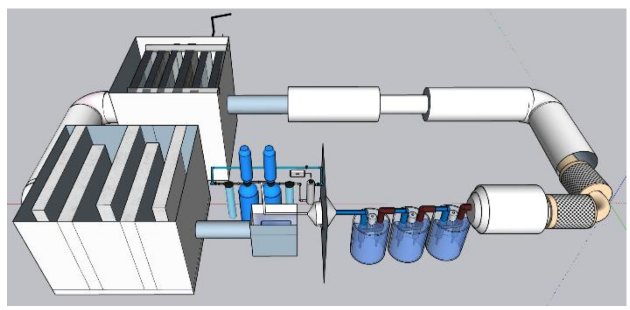


Figure 3.1: The 3D model of the prototype

1. A 3D model was created in SketchUp to guide construction, **as shown in Figure 3.1.**
2. The base, **depicted in Figure 3.2**, was built using a 56 × 80 cm wood plank supported by nine 14 cm legs.
3. A sand/gravel filter was constructed using a plastic container with layers: top gravel (distribution), sand (filtration), and bottom gravel (drainage).

Figure 3.2: The wooden prototype base.

4. An electrocoagulation system was built using a plastic container and 8 aluminum electrodes, spaced 1 cm apart, and connected with crocodile wires, **as shown in Figure** 3.3.
5. A UV sterilizer served as the biological disinfection stage.
6. A biochar adsorption stage was created using a plastic bottle with layers similar to the sand/gravel filter, but biochar replaced sand.
7. All stages were interconnected using pumps and hoses, **as shown in Figure 3.4**.

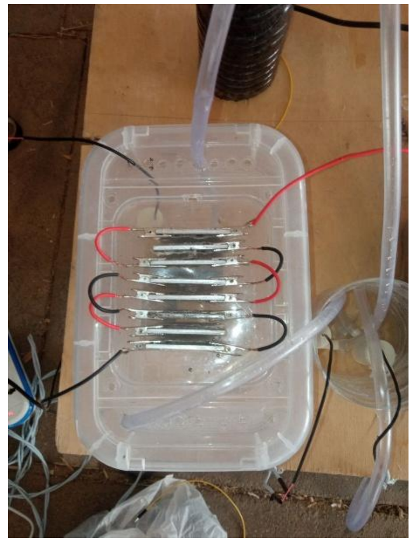


Figure 3.3: Wiring of electrocoagulation electrodes

Automation & Monitoring System

1. pH, TDS, temperature, and turbidity sensors were installed in the main container, **as shown in Figure** 3.5, to monitor water quality parameters, connected to an Arduino Uno.
2. A water flow sensor was added between the biochar filter and the main container to track treatment cycles.
3. Pumps were programmed for specific operation times per cycle, with two controlling water flow to either enter or bypass the electrocoagulation (EC) stage.
4. An Android app was developed using Kotlin and Jetpack Compose for real-time monitoring and system control.
5. Sensor data was transmitted via Firebase to the app, which also sent control actions to the system through the same server.

Figure 3.4: The full prototype with stages connected using pumps and hoses

Figure 3.5: The water quality sensors placed in the main container.

Safety Precautions

Some precautions were used during prototype building to ensure our safety. Lab coats and gloves were worn during all the processes to ensure protection from any material spills. Masks were used for any resulting harmful gas by mistake. Any wires were covered by tape to avoid direct touch. The UV lamp was insulated inside an opaque container to avoid direct exposure to its rays

Test Plan

A comprehensive set of tests was established to ensure the feasibility of the prototype to meet the design requirement:

1. The efficiency of the treatment processes was monitored over five complete treatment cycles for the same wastewater sample. Data on key parameters (e.g., pH, TDS, turbidity) were collected at each cycle. Linear regression analysis was applied to the results to determine the life expectancy of the treatment system.
2. The prototype's capacity was evaluated by measuring the volume of clean water produced every 10 minutes over a period of at least 1 hour. Additionally, the efficiency drop was monitored to assess system performance over time.
3. The system's energy consumption was calculated by measuring the electric current and voltage using voltage and current sensors. These measurements were taken during operation to determine the energy used per liter of clean water produced.

Data Collection

Measuring Tools

A graduated beaker was used to measure the volume of the used liquids with an uncertainty of ± 25 ml. A sensitive balance was used to measure the mass of used solids with an uncertainty of $\pm 5\times10^{-3}$ g. A ruler was used to measure the diameter of the mech with an uncertainty of 5×10^{-2} cm.

Results

Negative Results

During prototype construction, fractures in the main container and sand filter caused water leakage, which were repaired using wax. The TDS sensor interfered with the pH and turbidity sensors, necessitating transistors to deactivate the TDS sensor during pH and turbidity readings. Biochar was not compacted enough at first, which caused water to flow too rapidly.

Positive Results

1. **Efficiency of Treatment Processes**

The initial and final water quality parameters were measured for each cycle, and efficiencies were calculated, **as shown in** Error! Not a valid bookmark self-reference.. The total TDS removal efficiency was 81.54%, turbidity removal reached 99.08%, and pH stabilized at 7.5. **Figure 3.6** shows efficiency trends by the number of cycles, while **Figure 3.7** displays parameter readings across cycles. Applying linear regression analysis with an efficiency threshold of 30%, the life expectancy was estimated to be 276 cycles.

Table 3: The initial values of quality parameters and final values after each cycle.

Cycle	**Turbidity (NTU)**	**pH**	**TDS (ppm)**	**Temp (°C)**	**Turbidity Efficiency (%)**	**TDS Efficiency (%)**
Initial	656	7.43	2545	26.69	-	-
Cycle 1	127	7.8	1528.5	26.68	80.6	39.94
Cycle 2	49	7.6	1223.2	26.68	61.4	19.98
Cycle 3	28	7.5	979.8	26.71	42.9	19.9
Cycle 4	13	7.5	783.5	26.69	53.6	20.04
Cycle 5	6	7.5	469.7	26.70	53.8	40.05

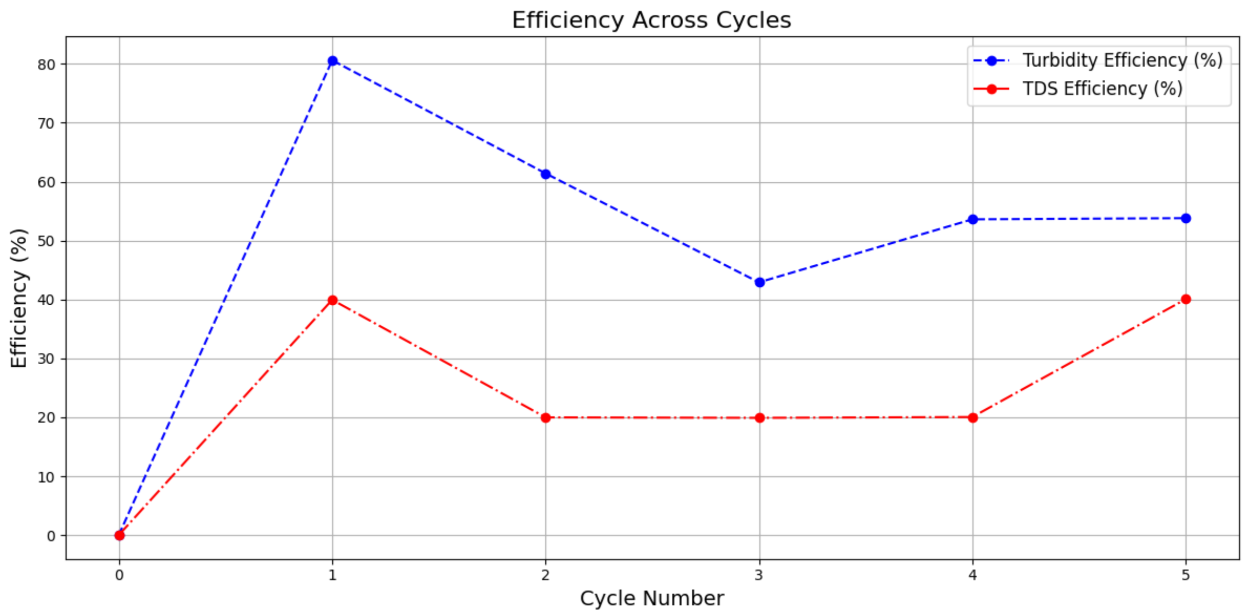


Figure 3.6: Efficiencies of the treatment system across cycles

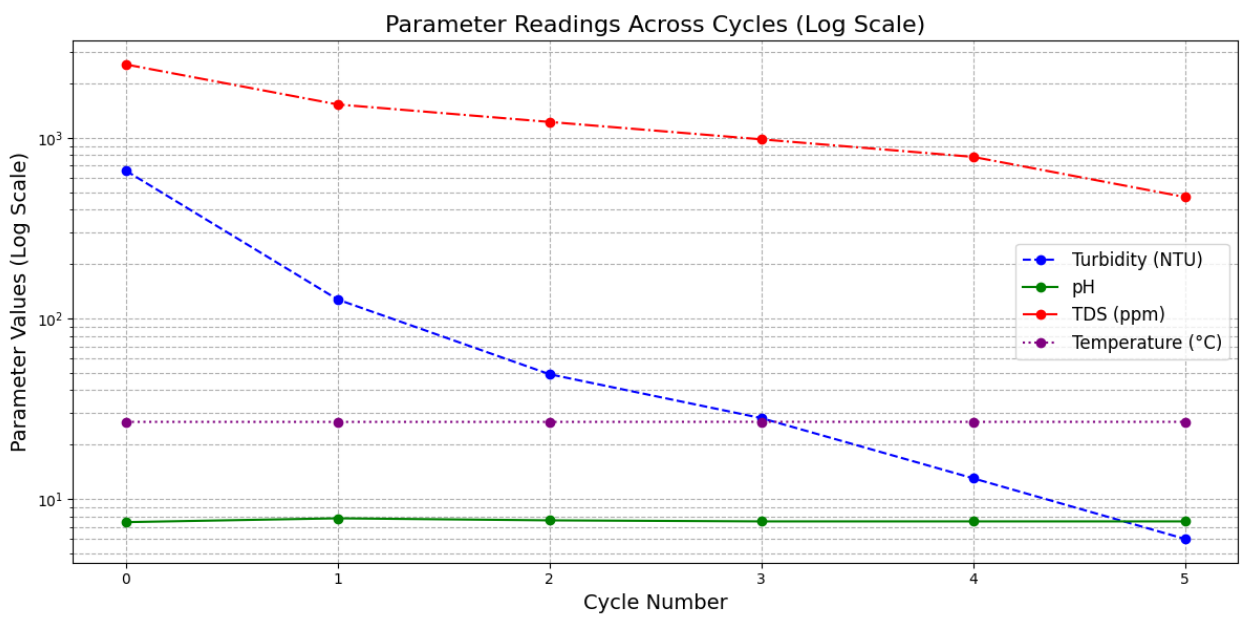


Figure 3.7: Parameter readings across treatment cycles.

2. Capacity of the Prototype

The production rate of clean water was calculated to be 0.0814 liters per 10 minutes. The prototype could treat approximately 0.49 liters of water per hour under continuous operation.

3. Efficiency Drop

The efficiency drop was tracked by measuring water quality parameters and calculating the difference in turbidity and TDS removal efficiencies between consecutive cycles. The largest efficiency drops occurred during early cycles indicating rapid initial performance degradation. However, the rate of decline stabilized in later cycles, suggesting the system reached a steady operational state.

4. Energy Consumption

The system consumed a total of 245.9 kJ in 6.145 hours, equivalent to 81.9 kJ per liter of clean water. **Figure** 3.8 illustrates energy and power consumption across cycles.

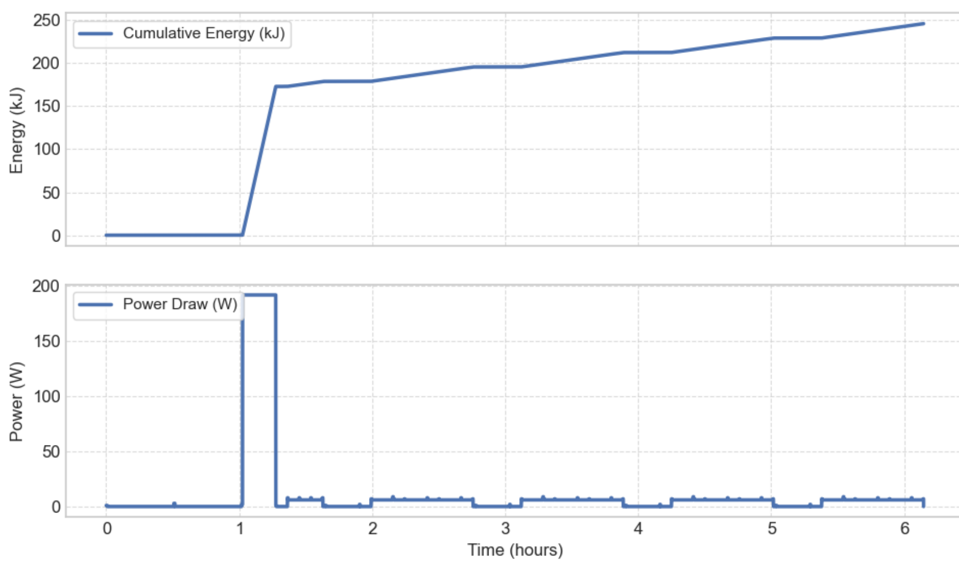


Figure 3.8: Power and energy consumption across treatment cycles.

4. Chapter 4: Evaluation, Reflection, Recommendations

Analysis and Discussion

Analysis

Purification Methods of Sand Filter

Sand filters remove contaminants via four primary mechanisms: physical straining, particle capture, electrostatic coagulation, and biological action.

Tannery wastewater usually contains excess leather trimmings which can block pumps if not removed. These trimmings are trapped in the pores between sand particles along with other relatively large substances using physical straining. The trimmings are specifically important as they contain collagen, which is a sticky substance that causes other particles smaller than the pores to adhere.

The second process consists of inertial impaction and adsorption (Maiyo et al., 2023, p. 2). Inertial impaction occurs when a flowing pollutant's inertia causes slight deviation from the water flow, leading to its collision and thus entrapment on the surface of sand particles. Molecules sometimes floc together due to van der Waal's forces leading to coagulants, which are then attracted and stuck to the surface of sand particles from adsorption. Adsorption can get very small particles too (*Filtration & Gravity Filters*, n.d.).

The third process depends on electrolytic charges. Colloids stay suspended in water as they have equal charge, so they continuously repel each other. As sand particles and flowing pollutants have opposite charges, they tend to attract each other which then leads to their charges neutralizing. This breaks the "repel" chain and causes these pollutants to clump and coagulate (Indira Gandhi National Open University, 2017, p. 3).

The fourth process depends on biological methods. Flowing wastewater carries bacteria, viruses, and other organic substances through the sand filter. A large percentage of these organisms are deposited on the top of the sand filter, which leads to the formation of a suitable environment for bacterial colonies.

Electrocoagulation: Mechanism & Optimization

After the sand filter has removed the large and small particles in the wastewater, it still contains a large percentage of chromium and other dissolved metals. The next stage, electrocoagulation, aims to decrease this by coagulating such pollutants.

In electrocoagulation, an electrical current is passed between an aluminum anode and cathode immersed in the wastewater. At the anode, aluminum oxidizes to release Al^{3+} ions, while water is reduced at the cathode to generate hydroxide ions and hydrogen gas. The anode/cathode reactions are shown in the next equation:

$$\text{Anode:} Al \rightarrow Al^{3+} + 3e^{-}$$

$$\text{Cathode:} 3H_2O + 3e^{-} \rightarrow \frac{3}{2}H_2 + 3OH^{-}$$

Several factors affect electrocoagulation. Firstly, electrode material. Aluminum was chosen due to its high efficiency in coagulating oils (Boinpally et al., 2023, p. 5) and the fact that it doesn't change the color nor taste of water unlike iron. Aluminum also leads to a lower increase in pH overall compared to mild steel. **As shown in Figure 4.1**, pH increased only by ~0.75 when using aluminum and by ~2 when using mild steel (Feng et al., 2007, p. 3).

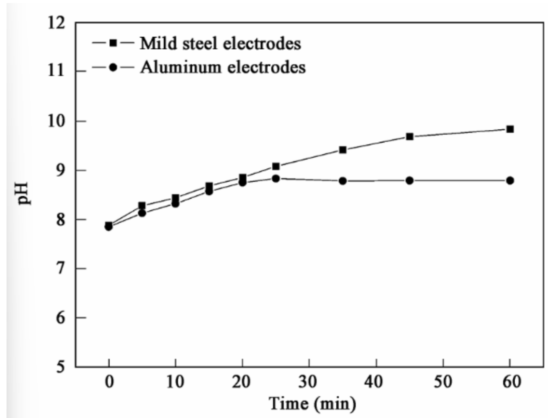


Figure 4.1: Comparison of pH increase from using aluminum electrodes and mild steel electrodes

Secondly, voltage and ampere. To get the optimal parameters for electrocoagulation, an engineer at Al-Rubiki's inactive treatment plant was asked. He stated that the voltage of 20 and an ampere of 7 is optimal. As we couldn't get a power supply fitting that exact description, we got a power supply with a 24 voltage and 10 ampere.

Thirdly, current density. Current density defines the number of ions being released into the solution. Increasing it means there'll be more ions to coagulate pollutants, but this is limited by the rate of coagulation of the ions and pollutants (Boinpally et al., 2023, p. 6). Since the total area of a single electrode is $110 \pm 2\ cm^2$, the area of the 8 electrodes used is $880 \pm 20\ cm^2$. Thus, the current density is:

$$J = \frac{I}{A} = \frac{8000\, miliamp}{880 \pm 20\, cm^2} = 9.1 \pm 0.2 \frac{mA}{cm^2}$$

According to literature, the optimal current density is $10 \frac{mA}{cm^2}$ (Touahria et al., 2016, p. 1).

Lastly, the distance between each anode and cathode was found to be optimal at 1 cm (Hussein et al., 2022, p. 12). Decreasing it causes the aluminum ions to collide degrading them, which decreases efficiency. Increasing it leads to the current facing higher resistance while traveling from the anode to the cathode, and thus lower efficiency.

Biochar Adsorption

The slow-gravity sand filter followed by the electrocoagulation removes virtually all suspended solids and colloids but leaves behind low-concentrations of chromium and industrial dyes. Industrial dyes and chromium are both toxic to plants and animals, thus it's important to also remove them.

As none of the previous stages focus on removing color, where dyes make up 30% of total tannery discharge, it's important that this stage can get rid of colorization efficiently. The high porosity of biochar makes it perfect for removing colors. Papers have shown that it can remove up to 95% of dyes (Haddad et al., 2022, p. 2,3).

Biochar captures chromium through diffusion into pores, electrostatic attraction and hydrogen bonding. Biochar also reduces Cr(VI) into the less harmful Cr(III) using the reductive groups on its surface using ion exchange (Zhong et al., 2023, p. 2,3).

Additionally, literature has found that at lower chromium concentrations, biochar adsorbs better, at 98% efficiency, due to the less competition over binding sites. Therefore, its position at the end of the prototype design is very fit (where most of the chromium has already been removed from the EC). Biochar also gets rid of any precipitates or particles formed during the electrocoagulation stage using its small pores.

To optimize the filter, several measures were taken. Firstly, the biochar filter was wrapped in aluminum foil to prevent light penetration and thus algae growth

(*Biochar and Activated Carbon Filters for Greywater Treatment – Comparison of Organic Matter and Nutrients Removal*, 2012, p. 11). Secondly, a separator was used between layers to decrease their mixing. Lastly, the biochar was grinded until it consisted of small rough particles, and all powder was removed.

UV Disinfection

Traditional water treatment systems utilize chemicals such as chlorine to kill bacteria. Although, as it is expected that the treated wastewater will be used for planting, using chlorine is inaccessible as it's poisonous to plants. Thus, using UV treatment instead is essential.

Chemical disinfectants decrease microorganisms by destroying their cellular structures. This leads to the cell's death due to its inability to metabolize. On the other hand, UV treatment damages nucleic acid which hinders the microorganism's capability to reproduce.

Nucleic acid consists of two components: purines and pyrimidines. UV, on average, causes more damage to pyrimidines. The damage comes in 3 main forms. Pyrimidine dimers form due to the presence of covalent bonds between adjacent pyrimidines. Photoproducts are similar to dimers. Protein-DNA cross-links are covalent bonds between proteins and DNA strands.

By positioning the UV unit as the final treatment step after both sand and biochar filtration have removed virtually all large and fine particulates and centering the lamp inside its holding tube, called the quartz sleeve, so that water flows evenly around it, we ensure that UV light isn't blocked by debris and that every microorganism passes within close, uniform distance of the lamp. This maximizes disinfection efficiency as UV intensity decays with distance (*Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule*, 2006, p. 44, 46).

Effective Particle Size

Effective particle size, or D_n, is used to measure the amount of a sample that would pass through a sieve of diameter D_n. That is, D_{10} is the maximum diameter length of the smallest 10% particles of a sample by weight. This parameter is used in sand and biochar filters to calculate the uniformity coefficient, which tells us how close the sizes of the particles are.

As calculating D_n requires unavailable equipment, an approximation was calculated. It's assumed that all sand particles have the same weight, thus D_n would be referring to the $n\%$ of particles with a diameter less than or equal to D_n.

The coefficient of uniformity is calculated by the following equation:

$$C_u = \frac{D_{60}}{D_{10}}$$

To calculate D_{60} and D_{10}, two samples of 100 grains of biochar and sand were obtained from the filters. Then, a digital vernier caliber was used to measure each grain's largest diameter to obtain 2 datasets, **shown in Figure** 4.2.

These values were inputted into Excel and, using the *PERCENTILE.EXC* function, their $10th$ and $60th$ percentiles were computed. In the case of the sand particles, $D_{S60} = 0.596$ and $D_{S10} = 0.272$. In the case of the biochar, $D_{B60} = 1.99$ and $D_{B10} = 1.111$. Thus,

$$C_S = \frac{D_{S60}}{D_{S10}} = 2.191,\ C_B = \frac{D_{B60}}{D_{B10}} = 1.791$$

Literature has found that for all granular media filters (such as slow sand filters and biochar filters), C should optimally be in the range between 1.5 to 2.5 (Centre for Affordable Water and Sanitation Technology (CAWST), 2009, p. 98).

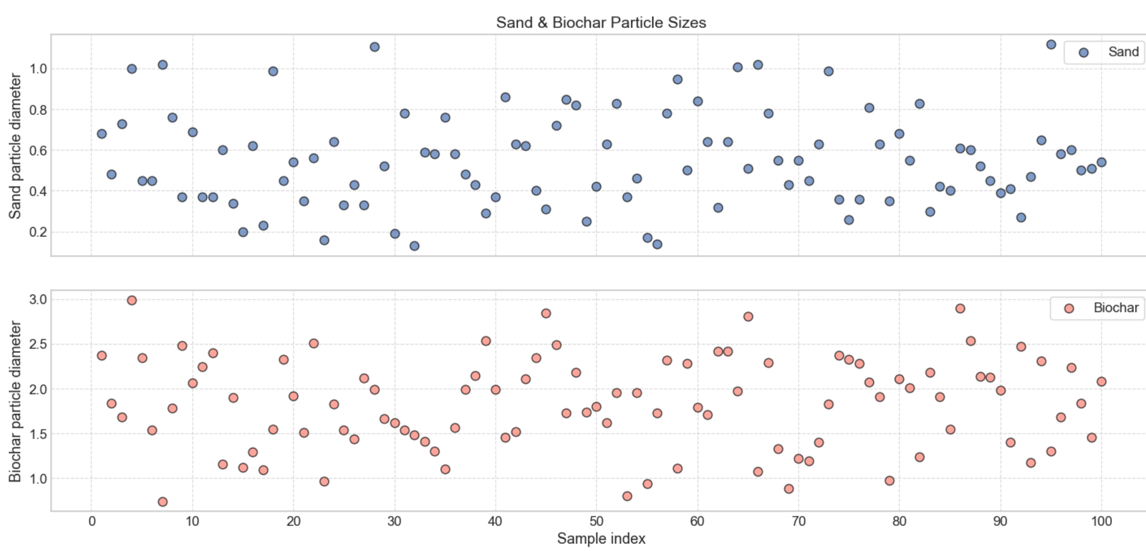


Figure 4.2: Size datasets of both sand and biochar

Conclusions

To sum up, the selected problem to be solved through this project was water scarcity and improper wastewater disposal hindering land reclamation near the Rubiki Industrial Zone, Badr City. The solution consisted of 4 physical and chemical treatment stages. Electrocoagulation, renowned for its high efficiency in removing contaminants that are challenging to address through filtration or chemical treatment, played a vital role in the prototype alongside sand filtration, biochar, and UV stages. Despite some negative results, the prototype successfully met all the design requirements, reducing salinity to 469.7 ppm, turbidity to 6 NTU, and maintaining the pH level at 7.5. Compared to prior solutions, like New Cairo and Bahr El-Baqar wastewater treatment plants, the project uses easily accessible and recycled materials for eco-friendly and more cost-effective results. By combining the strengths of earlier methods while addressing their limitations, this project delivers a practical and sustainable solution for reducing salinity, TDS, turbidity, and pH, offering significant potential for environmental sustainability.

Recommendations

Real-life Application

Figure 4.3: Al Rubiki Industrial Zone, Badr City.

The Rubiki Industrial Zone, **shown in** Figure 4.3, located in the Cairo-Suez district of northern Badr City, has been selected as the recommended site for project implementation due to its high levels of pollution. This zone includes an area known as The Leather City, which contains numerous tanneries that produce large quantities of wastewater laden with pollutants like chromium, a toxic metal commonly used in the leather tanning process. This wastewater is currently not reusable due to its contamination levels. The proposed solution involves replicating the prototype's filtration and smart automation system to treat the wastewater onsite. Once treated, the water will be redirected for irrigating non-fruit-bearing trees, which do not require high water purity. This approach not only addresses water pollution but also supports environmental improvement by helping reduce greenhouse gas emissions in the area. The integration of this system aims to promote sustainable industrial practices and enhance the ecological health of Rubiki Industrial Zone.

Centrifugal Sludge Pump (Slurry Pump)

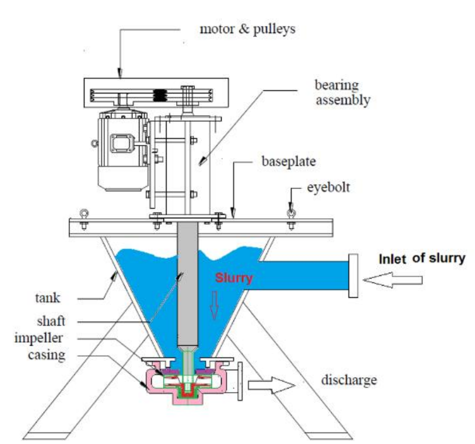


Figure 4.4: Structure of a centrifugal sludge pump

Using a centrifugal sludge pump is recommended at the bottom of the EC tank to remove the dense flocculated wastes during operation, **as shown in Figure 4.4**. During the operation of the pump, the impeller converts electric energy from the motor to rotational kinetic energy. This motion creates a low-pressure zone at the area where the sludge is accumulated. This allows the sludge to flow through the suction pipe to an external tank where the sludge is then taken and removed safely. The pump will be connected to the smart system of water treatment where a sensor will sense the sludge level. When the sludge level gets low the pump will be turned off automatically to avoid excess water flow through the pump. Sensors monitoring sludge levels can reduce unnecessary pump operation, saving up to 20–30% of energy costs associated with continuous pumping.

Magnetic Biochar

In the water filtration system, we encourage using magnetic biochar instead of the normal biochar stage. Magnetic biochar is synthesized by incorporating transition metals and their oxides, especially Fe_3O_4, nanoparticles into biochar. It enhances adsorption capacities and facilitates easy separation from treated water and thus decreasing the inorganic contaminates, such as heavy metals, and organic contaminants, like dyes, more efficiently. Magnetic biochar derived from woodchips has achieved a maximum Cr(VI) adsorption capacity of 80.96 mg/g (Santhosh et al., 2020), while the normal biochar has a capacity of 50 mg/g. In addition, the magnetic biochar maintained high removal efficiency over multiple cycles, which indicates its cost-effectiveness. The adsorption mechanism involves electrostatic attraction, then reduction of Cr(VI) to Cr(III), and complexation with functional groups on the biochar surface, where the surface of the biochar has functional groups, like -OH, -COOH, that can bind to Cr(III) to form complexes.

Sand Rewashing

Sand rewashing is a process that restores the filtration capacity of sand by removing contaminants accumulated during use. Three main ways of rewashing process, backwashing, air scouring, and chemical methods. Backwashing uses high-pressure water, while air scouring employs air to dislodge impurities. Chemical treatments, such as acidic or alkaline solutions, help dissolve and remove organic and inorganic contaminants, especially heavy metals like chromium. To remove heavy metals the alkaline method is preferred, which involves using chelating agents like EDTA or citric acid. Their combination restores up to 90% of the sand's original adsorption capacity. Rewashing reduces the need for new sand by up to 50% annually, leading to cost savings of 30-50%. Sand rewashing ensures continuous filtration efficiency, making it a cost-effective and eco-friendly recommendation.

Recommendations for Future Teams

We recommend for other teams working on wastewater treatment challenges to use a Centrifugal Sludge Pump (Slurry Pump), focus more on real-life applications, and consider using Magnetic Biochar instead of natural biochar. Additionally, we suggest incorporating sand rewashing techniques to improve filtration efficiency. We also recommend adding a stage that releases specific non-pollutant chemicals capable of purifying water by reducing BOD and COD parameters. Furthermore, we encourage placing greater emphasis on the feedback system and its circulation to enhance overall performance.

Likewise, we suggest implementing an accurate monitoring system that adheres to national standards for drinkable water while utilizing efficient lab sensors to minimize result uncertainties. Finally, we remind all teams of the critical importance of safety precautions when handling chemicals, regardless of their toxicity levels, as exposure can lead to significant health risks.

Project's Positive Influence

Our team at STEM school has had a real-life changing event while designing and constructing a real-life project and a prototype for an air filter. This project has not only helped us to understand scientific and engineering concepts profoundly, but it has also improved our abilities to work together and communicate effectively. This project has opened up a whole new world of scientific exploration, encompassing fields such as physics, chemistry, and the combination of them both. We had a better understanding of adsorbent materials and how to improve the future of this field. The project also improved our soft skills such as communication, creativity, and teamwork

Learning Outcomes

L.O	Concepts	Connection
CH.2.08	Electrolysis, Factors affecting the types of liberated substance	Electrolysis of water was applied in electrocoagulation, using four adjacent aluminum electrolytic cells to remove heavy metals and contaminants.

CH.2.09	Electrode potentials	Reduction and oxidation potentials were used to determine the best type of electrode for electrocoagulation.
PH.2.08	Electromagnetic induction	Electromagnetic induction was utilized in relays to control water pumps via electric signals.
PH.2.16	Bipolar Transistor (PNP) and (NPN), Use of the transistor as a digital switch	PNP and NPN transistors were used as digital switches to activate/deactivate the TDS sensor, preventing interference with other sensors and improving accuracy.
PH.2.10	DC Motot	Used water pumps integrated DC motors to pump water from a container to another.
MA.2.10	Percentiles	The concept was used to distribute the datasets containing the diameters of sand particles and biochar into ranked percentiles.
CS.2.05	Mobile App Structure, Android Studio	An Android app, developed using Kotlin and Android Studio, was created to monitor and control the water treatment system.
CS.2.06	Layouts, Views	Layouts and Views were used to make the user interface of the application, which monitored and controlled the system.
BI.2.09	Hormonal Control of Cycles, Feedback Systems	A feedback system was implemented in the prototype to ensure treated water meets the defined design thresholds.
ME.2.05	Power	The concept was used to calculate the total energy consumption of the treatment system.

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