PERFORMANCE EVALUATION OF CONSTRUCTED WETLAND FOR TERTIARY TREATMENT

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Degree of Master of Science

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Dissertation submitted in partial fulfilment of the requirements for the
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Declaration

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The above candidate has carried out research for the Master of Science in Environmental Engineering and Management under my supervision.

Name of the supervisor: Prof. M.W. Jayaweera

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Abstract

The textile industry in Sri Lanka is a leading apparel manufacturer worldwide, with a state-of-the-art dye house and a well-equipped automated laboratory with physical and washing test facilities. The dye plants inside the factory deploy high-tech methods such as exhaust dyeing (hank and high pressure) and piece dyeing (continuous dying) for polyester, nylon, and cotton fabrics. A chemical wastewater treatment plant (1,000 m^3/day) has been installed to treat the factory's wastewater (process wastewater and domestic wastewater). The quality of the treated effluent meets the tolerance limits for industrial wastewater discharge into inland surface waters, reducing environmental harm. As requested by the Central Environmental Authority (CEA), a constructed wetland and fishpond have been incorporated into the existing wastewater treatment facility to improve the treated wastewater quality and ensure that no harmful chemicals remain in the treated wastewater discharged into a nearby waterway. The wetland is a sub-surface flow type where no water column is maintained, and the wetland area is around 1acre. *Phragmites spp*. (*Phragmites karka*) has been planted. The medium in which plants are grown comprises broken burnt clay disposed of from tile factories. A 50% void ratio was maintained for the easy flowing of wastewater through the wetland. The zigzag configuration is maintained throughout the wetland to avoid the short-circuiting phenomenon. The research study showed removal efficiencies of 72.3%, 51.8%, 47.2% 25%, and 73% for the contaminants COD, BOD, TSS, TKS, and TP, respectively. The temperature and pH almost remain the same with little variations. data showed faecal coliform levels were less than 2 MPN/100 ml throughout the data collection period. The study suggests that, if appropriately operated, constructed wetlands might have been effectively utilized for tertiary wastewater treatment under local circumstances. As a result, constructed wetlands can be included in the treatment process to modify existing underperforming wastewater treatment plants as well as a sustainable green concept.

Keywords - Constructed wetland, industrial, wastewater, treatment, efficiency

List of abbreviations

APHA	- American Public Health Association
BOD	- Biological Oxygen Demand
CEA	- Central Environmental Authority
COD	- Chemical Oxygen Demand
CWs	- Constructed Wetlands
DO	- Dissolved Oxygen
DO_5	- Dissolved Oxygen after 5 days
EPL	- Environmental Protection License
FVFCW	- French Vertical Flow Constructed Wetland
FWSCW	- Free Water Surface Flow Constructed Wetland
GDP	- Gross Domestic Product
HFCW	- Horizontal Flow Constructed Wetland
HLR	- Hydraulic Loading Rate
HRT	- Hydraulic Retention Time
NEA	- National Environment Act
NH_4^+	- Ammonium Nitrogen
NWSDB	- National Water Supply and Drainage Board
OWTSs	- Onsite Wastewater Treatment Systems
SSFCW	- Subsurface Flow Constructed Wetland
TDS	- Total Dissolved Solid
TKN	- Total Kjeldahl Nitrogen
TSS	- Total Suspended Solids
UNEP	- United Nations Environment Program
VFCW	- Vertical Flow Constructed Wetland
WWTPs	- Wastewater Treatment Plants

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1. INTRODUCTION

1.1 Background of the study

Water is the crucial factor for the sustenance of human survival, healthy ecosystems, and socio-economic development and it is the core of sustainable development. The increasing need for water is a global issue; hence significant attention is paid to sustainable water use. The rapid growth of the population has resulted in globalization, industrialization, and unprecedented urban expansion which results in water stress (Kivaisi, 2001). Several countries located in semi-arid and arid regions in the world are suffering from water scarcity and most of them are developing countries (Heyns, 2021; Kivaisi, 2001). According to the estimated data, around 2 billion people do not have access to safe water (Sundaravadivel & Vigneswaran, 2001). In order to meet the high demand for water, most people tend to exploit reserves. The most severe problem that arises with the exploitation of reserves is that they are not replenished sufficiently, thereby causing a depletion of water reserves as well.

The shortage of clean water in developing countries is intensively challenging because the quality of available water resources in developing countries is deteriorating due to pollution. The rapid growth of industrialization across developing countries may result in rising amounts of emerging contaminants in water resources as well (Doltade et al., 2022). The major sources of water pollutants are identified as municipal sewage and industrial wastewater (Kivaisi, 2001). The pollutants in industrial wastewater include biodegradable organic matter, inorganic chemicals, organic chemicals, and toxic substances. The most common practice in handling industrial wastewater is to discharge it into aquatic environments such as oceans, rivers, and lakes (Edokpayi et al., 2017). These poorly regulated practices resulted in water contamination: hence, unsuitable for human consumption or any other water use. Also, these are the root causes of water-borne diseases.

Among the wastewater from industries, effluent from the textile industry is the leading contributory factor to water pollution. Sri Lanka is the leading exporter of apparel and textile products in the world, is of utmost importance to evaluate the quality of the effluents discharged from the related industries to the environment. During the process of textile manufacturing, various types of dyes and chemicals are used. Textile effluents consist of several synthetic dyes and toxic chemicals (Kumar & Saravanan, 2017). The processes of dyeing, rinsing, bleaching, and finishing discharge large amounts of wastewater resulting in liquid waste rich in chemicals (Liu et al., 2011).

Generally, biological, physical-chemical, and combined treatment processes are applied to the textile wastewater before its discharge into the surface waterbody or municipal sewage (Kumar & Saravanan, 2017; Liu et al., 2011). The primary and secondary wastewater treatment processes undertake mainly following the steps 1. mixing and equalizing the flow fluctuations, 2. screening and oil and grease trap 3. coagulation, 4. flocculation, and 5. settling tank (Desai & Mehta, 2014; Kumar & Saravanan, 2017; Liu et al., 2011). Excessive levels of total dissolved solids (TDS), toxic metals, and high colour are the major responsible factors to reduce the capacity of self-degradation of pollutants in textile wastewater (Saratale et al., 2011). The conventional methods used for dye removal in textile wastewater include chemical oxidation, coagulation and adsorption process, and biological processes (Desai & Mehta, 2014). None of these unit operations are able to remove the dye content in the textile wastewater individually. The dyes are in the form of inorganic in nature which is toxic to the microorganisms used in the biological treatment processes; hence decolorization of dyes cannot be performed alone with biological processes. The dyes can be either soluble or insoluble. The coagulation technique is more suitable for insoluble dyes. However, the activated carbon technique can be used only for soluble dyes.

The advanced textile wastewater treatment processes include various techniques such as adsorption, coagulation, membrane separation, floatation, ozonation, ion exchange, evaporation, and crystallization (Kumar & Saravanan, 2017). The performance comparison of these techniques depends on operational issues, water quality, and the projected cost for the construction and operation of a full-scale facility.

In recent decades, the need for tertiary treatment to remove the excessive levels of pollutants, contaminants, and salts from textile effluents is gaining attention to reduce surface water contamination. Further, the capability to meet the permissible levels of contaminants or pollutants according to the statutory requirements should be focused on to determine the effectiveness and efficiency of tertiary treatments in terms of final effluent quality. The selection of a tertiary treatment process should be carried out in the aspects of quantifiable criteria and non-quantifiable criteria. The quantifiable criteria include 1. Capital cost, 2. Energy use, 3. Availability and reliability, and greenhouse gas emissions. The non-quantifiable criteria include 1. Reliability and maintainability of technology, 2. The flexibility of technology, and future technology developments.

The future trends in implementing suitable tertiary wastewater treatment in the textile industry focus on sustainable solutions mostly. The past two decades showed dramatic changes in water treatment approaches where the need for tertiary treatments for textile wastewater is comprehensively analyzed in terms of lower capital and operational maintenance cost, efficiency rates, operational procedures, final effluent quality, and waste production at the end of the process. Previous research studies have shown that the performance of constructed wetlands as a tertiary treatment of textile wastewater is a successful initiative (Bulc & Ojstršek, 2008; L. C. Davies et al., 2005; Mbuligwe, 2005; Yalcuk & Dogdu, 2014). The constructed wetlands are identified as a sustainable and cost-effective treatment alternative with promising results for contaminant removal in textile wastewater.

Therefore, the implementation of the constructed wetland as a tertiary treatment for the textile wastewater will be a sustainable solution to enhance the effluent water quality.

1.2 Research need

The leading apparel manufacturers in Sri Lanka with higher production capacities consist of state-of-the-art dye houses and automated laboratories with physical and washing facilities. The dye plants of those factories deploy high-tech methods such as exhaust dyeing (hank and high pressure) and piece dyeing (continuous dyeing) for polyester, nylon, and cotton fabrics.

The maintenance of environmentally friendly solutions during various stages of production and balancing the equilibrium of profits, environment, and people are the key concept which is well-integrated into the companies' ethics to minimize long-term environmental damage. Presently, the relevant stakeholders are taking measures to reduce environmental damage, which includes ways to conserve energy and water.

In order to minimize harm to the environment, modern wastewater treatment plants (WWTPs) have been constructed and implemented to treat wastewater from textile factories. The treated wastewater quality is to be checked against the tolerance limits stipulated by Central Environmental Authority (CEA) and other relevant stakeholders. Textile effluent contains dyes, pigments, surfactants, grease and oil, metals, sulfate, and chloride. Considering the quality of the treated textile wastewater effluents, tertiary wastewater treatment mechanisms are of the utmost importance based on the sensitivity of the environment in which the treated effluents are disposed of.

Further, the treatment efficiency can be enhanced with tertiary treatment interventions. Constructed wetlands have emerged in the recent past as tertiary treatment. The CEA is also interested to intervene CWs with extra measures to further enhance the effluent wastewater quality from the WWTPs such that no toxic compounds are disposed of to the nearby water resources.

Secondary treatment may not be sufficient and must combine a polishing step before discharging. Many industries have used various traditional and novel wastewater treatment technologies to achieve the CEA of Sri Lanka's wastewater treatment discharging regulations. As a developing country, in decision-making in providing clean water and wastewater disposal, the most crucial criterion is economical. Hence, when considering sustainable wastewater treatment systems, it should focus on approaching local needs requiring minimal investment and less sophisticated operation (Clarkson et al., 2010). Thus, in Sri Lanka, there is much interest in using cost-effective CW technology as a tertiary treatment option (Rathmalgoda, 2017). Therefore, constructed wetlands can perfectly apply to our treatment process as an ecological sustainable engineered system that supports human well-being.

The proposed study will assess the efficiency of the CW to enhance the effluent quality of the textile wastewater. Further, the CEA and other relevant stakeholders can rely on the results of this study when proposing the CW as a tertiary wastewater treatment process for other factories appropriately.

1.3 Justification of the study

Textile is one of the main contributors to water pollution (Shehzadi et al., 2014). Wastewater produces during fabric processing is one of the most obscene pollutes of water and soil (Desai & Mehta, 2014). Moreover, the chemicals in textile wastewater seriously affect human health due to their toxic, mutagenic, or carcinogenic nature (Bafana et al., 2009). Furthermore, they can degrade environmental systems' by receiving dye-rich textile effluent in surface water that suffers from light penetration and develops poor oxygen conditions (Khan & Malik, 2014). Correspondingly, the presence of colour in the textile effluent decreases the aesthetic value of the receiving system.

Therefore, it is helpful to acquire a tertiary treatment for wastewater from the textile industry to enhance the treatment efficiency; such that the CW is proposed. However, it may have some limitations also. Toxic compounds present in textile effluent can inhibit plant growth and microbial proliferation, consequently affecting remediation efficiency (Kabra et al., 2013; Khandare et al., 2012; Shehzadi et al., 2014). The combined application of plant and contaminant-degrading bacteria has been proposed recently to reverse the effect of these toxic compounds (Arslan, 2017; Khandare et al., 2012). The effluent from the textile manufacturing companies is mostly released into the nearby freshwater system and sensitive water bodies. Further, wastewater from dyeing units is often rich in colour, containing residues of reactive and acid dyes, with high COD, BOD, and TDS with some complex organic and inorganics components. The chemical wastewater treatment plant reduces BOD and COD to acceptable levels for discharge. However, the CEA is searching to further enhance the effluent water quality with the incorporation of green concepts and ensure that no toxic compounds are presented.

The research study selects a factory where a wastewater treatment plant is already functioning. The existing WWTP with a capacity of 1,000 m^3/day has been installed. The wastewater treatment plan layout is depicted in Appendix 1-1. It processes wastewater and domestic wastewater generated from the factory. The quality of treated effluent complies with the tolerance limits for industrial wastewater discharge into inland surface waters.

The proposed study will evaluate the performance of a CW which takes the treated effluent from the wastewater plant as the influent. Nowadays, wastewater management focuses on new developments to convey solutions for the constant supply of clean water, water pollution control, water recycling, and reuse while targeting environmental protection. Therefore, this study plays a critical role in assessing the efficiency of the constructed wetland (CW) because the results of the study can be used for future interventions to be taken by the CEA such that the water quality of the water sources can be protected.

2. LITERATURE REVIEW

2.1. Legal and regulatory framework applicable to wastewater treatment

2.1.1. Existing policy framework

Wastewater should be treated and disposed of with minimal environmental impact to reduce the impact of the wastewater on the ecosystem and water scarcity. Therefore, to obtain the benefits from the treatment process, disposal mechanisms should be regulated successfully and implemented in a legal framework. It will help to achieve the sustainable development goals stipulated by United Nations (UNEP, 2015). Water regulations and technology were initiated by the International Water Supply Association in 1947. Over the last decade, the constant growth in the amount of untreated wastewater has led to treat partially before discharge into the ground or waterbody. Therefore, monitoring and water quality assessing schemes should be implemented separately according to the receiving water bodies.

Central Environmental Authority (CEA) serves as a regulatory authority and has established the guidelines for wastewater disposal. There are numerous environmental legislations and standards for managing wastewater collection, treatment, and disposal. The National Environment Act (NEA) no. 47 of 1980 (revised in 1988 and 2000) is the most critical overarching legislation. It covers wastewater management and includes legislation to preserve the environment and control pollution. Within NEA, several rules and regulations oversee compliance with wastewater discharge. Under the legislation, CEA requires a Cabinet-approved committee to minimize water pollution from industries into receiving water bodies. Furthermore, the law was mandatory for secondary treatment to discharge wastewater for agricultural purposes.

2.1.2. Legal framework for wastewater treatment

Legal provisions in relation to different acts, legislations, regulations, and guidelines on wastewater treatment and disposal in Sri Lanka are as follows;

1. The irrigation ordinance (No. 32 of 1946 with amendments),

2. The National Water Supply and Drainage Board Act (No. 02 of 1974 as amended)

In addition, following legislations related to water and wastewater management is initiated by the respective parties mentioned as follows:

1. Establishment of a National Water Resource Council: The water resource secretariate has been established to acknowledge all water-related apprehensions inclusively. This acts as a high-level advisory group, including all government agencies and stakeholders
2. Establishment of a Ministry of Water Resources: The Ministry of Water Resources has been established to supervise the water resource council.

General discharge guidelines must be followed when specific tolerance limits are not available. The National Environmental (Protection and Quality) Regulation No. 1 of 1990 (Gazette extraordinary no. 595/16, dated February 2, 1990) establishes the tolerance limits for industrial and domestic effluents. These standards are currently being revised. Tolerance limits for wastewater from the textile industry being discharged into inland surface water were indicated in Table 2-1.

Table 2-1: Tolerance limits for wastewater from the textile industry being discharged into inland surface water [National Environment (Protection and Quality) Regulations as stipulated in the Gazette Extraordinary No. 1534/18 of 02.01.2008)

No.	Parameter	Unit, Type of limit	National standards	Interim standards
1	pH at ambient temperature	-	6.5 to 8.5	6.5 to 8.5
2	Temperature	°C, max	40 (measured at the site of sampling)	40 (measured at the site of sampling)
3	TSS	mg/L, max	50	500
4	BOD	mg/L, max	60	200
5	Colour	Wavelength range	The maximum spectral absorption co-efficient	The maximum spectral absorption co-efficient
		Yellow	436 nm (7 m^{-1})	400-499 nm (7 m^{-1})
		Red	525 nm (5 m^{-1})	500-599 nm (5 m^{-1})
		Blue	620 nm (3 m^{-1})	600-750 nm (3 m^{-1})
6	Oil and grease	mg/L, max	10	30

No.	Parameter	Unit, Type of limit	National standards	Interim standards
7	Phenolic compounds	mg/L, max	10	5.0
8	COD	mg/L, max	250	600
9	Sulfides	mg/L, max	2.0	2.0
10	Ammoniacal Nitrogen	mg/L, max	60	50

An Environmental Protection License (EPL) should be obtained from the CEA by the hotels and industries that are involved in sustainable wastewater treatment systems. Most treatment plants discharge treated wastewater to nearby watercourses rather than directly releasing it for agricultural purposes. Industries and livestock farmers also use their wastewater with minimal or no treatment in their agricultural farming.

2.2. Industrial wastewater

Industrialization is the key to economic development as well as it is the root cause of environmental pollution. There are various types of industries that directly or indirectly pollute the environment. Different types of raw materials, products, and domestic wastes contaminate the water sources because of uncontrolled disposal measures. Industrial wastewater is generated due to raw-material processing and manufacturing with the participation of humans (W. J. Ng, 2006).

There are different types of industrial wastewater from different industries such as iron and metal, textiles and leather, pulp and paper, petrochemicals and refineries, chemicals, non-ferrous metals, microelectronics, and mining. The pollutant content in each type of wastewater differs from one to another. The water pollutants in the wastewater from the iron and steel industry include BOD, COD, oil, metals, acids, phenols, and cyanide (Yi, 2009). BOD, COD, solids, and chlorinated organic compounds can be found in the wastewater generated from the pulp and paper industry. Water pollutants such as BOD, COD, mineral oils, phenols, and chromium are included in the wastewater from the petrochemicals and refineries industry. The wastewater generated from the chemicals industries consists of COD, organic chemicals, heavy metals, suspended solids, and cyanide. The wastewater generated from non-ferrous metal manufacturing industries contains fluorine and suspended solids. COD and organic chemicals can be found in the wastewater generated from the microelectronics industry and suspended solids, metals, acids, and salts can be found in the wastewater generated from the mining industries (Yi, 2009).

Industrial wastewater can be either inorganic or organic (Yi, 2009). Inorganic industrial wastewater contains suspended matter mostly with extremely toxic substances. Therefore, these effluents should purify before discharge to ensure that the toxic compounds are not released into the environment.

Organic industrial wastewater is generated from industries where organic substances are utilized for manufacturing processes. Therefore, the necessity of biological treatments has arisen when treating organic industrial wastewater. Organic industrial wastewater is generated from leather factories, paper manufacturing plants, the oil refining industry, and textile industries (Yi, 2009). Textile wastewater is an emerging issue in Sri Lanka, as the textile industry is one of the major contributory fields to the Sri Lanka economy. After the industrial revolution, newer technologies intervened in the textile industry. Hence, textile wastewater quality and the most appropriate mechanisms to treat the effluent before discharging it into the environment are to be evaluated.

Many European nations are currently leading the field of wastewater treatment technology. The common practice of the Europeans is to discharge the pre-treated wastewater either into the municipal wastewater treatment plants or communal sewerage. South Asian and Sub-Saharan African countries have relatively low levels of wastewater treatment technology. Also, research conducted by the United Nations University Institute for Water, Environment, and Health, has found that the way countries treat their generated wastewater varies correspondingly to their income (Malik et al., 2015). In his research, he presented the percentage of wastewater treatment quantitatively as 70% for high-income countries, 38% for upper-middle-income countries, 28% for lower-middle-income countries, and 8% for low-income countries.

United Nations Environment Program's (UNEP/UN-HABITAT) Sick Water Report (2010) stated that up to 90% of untreated wastewater flows are produced in densely inhabited coastal areas, resulting in considerable contamination levels of rivers and lakes, groundwater, and coastal waterways. The consequences of deoxygenated 'dead zones' are growing, posing a threat to fisheries, livelihoods, and the food chain. Wastewater produced by agriculture and industrial operations creates a significant burden for downstream users. Its challenges result from water contamination by heavy metals, artificial organic pollutants, and micro-pollutants such as pharmaceutical products, pesticides, human waste, livestock manure, and chemicals.

2.3. Textile wastewater

The textile and apparel industry plays an important role in the Sri Lankan economy. The complexity of the modern world resulted in higher demand for textiles. Therefore, the required capacity for textile manufacturing is considerably high and the textile industry is one of the major contributors to textile wastewater. The pollution caused by textile wastewater effluent is a threat to public health and is rising as a worldwide issue. Furthermore, it is the main reason to look into new initiatives for environmental restoration concepts in terms of economic and ecological perspectives.

The amount of textile wastewater generation is different according to the unit operations of the manufacturing processes. The processes include fabric mills, garment washing, and dyeing factories. Textile wastewater contains dyes, chemicals (complex organic compounds) (Arachchige et al., 2019) bleaching agents, and salts with different contaminants. The textile manufacturing process needs water in large quantities based on the types of machinery used. Hence, the amount of wastewater generated is also high. An average-sized textile mill with a production of 8,000 kg of fabric per day consumes 16. million Liters of water (Khan & Malik, 2014). There are direct and indirect consequences as a result of discharging textile effluents into the environment. The direct consequences are deterioration of aesthetic appearance, blockage of sunlight penetration to the water bodies, disturbance to the flora and fauna of the ecosystem, an increase in the degree of groundwater pollution, and depletion of dissolved oxygen of receiving water bodies. Eutrophication, adverse effects on aquatic life, acceleration of genotoxicity and micro toxicity effects, cause of human illness are some of the indirect consequences.

2.3.1. Characterization of the textile wastewater

According to (Gozálvez-Zafrilla et al., 2008; Ranganathan et al., 2007) wastewater generation per ton of finished textile product is approximately 200-250 m^3. It approximately contains COD 100 kg per ton of fabric (Jekel, 1997). Khan & Malik, 2014, in their research has found typical factory effluent had COD 5000-6000, total dissolved solids (TDS) 52,000, TSS 2,000 mg/L, and pH 9. In their research, they have shown that the effluents contain a high organic load and BOD, COD, and other dissolved solids. Heavy meatal micronutrients also can be found in the textile wastewater (Khan & Malik, 2014).

2.4. Wastewater generation and treatment in Sri Lanka

Access to safe drinking water and acceptable sanitation is a tremendous challenge in highly populated areas of Sri Lanka. While Local Councils service a small percentage of municipalities, many rural townships are not connected to the sewer system. Colombo, Galle, Jaffna, and Kandy face severe environmental pressures due to improper sewerage, industrial effluents, and solid waste (Bandara, 2003).

In Sri Lanka, the total annual water resources for agriculture, industry, and domestic purposes, are only used 20%. The agriculture sector uses nearly 96% of this, and the remaining 4% is shared equally by the domestic and industrial sectors (ADB, 2002). ADB (2002) indicated that 70% of urban water returns wastewater. Cities adjacent to a river or sea directly dispose of wastewater into the nearest waterbody. For example, about 75% of Colombo city’s wastewater was pumped into the Kelani River (Jayakody et al., 2006). The river water is consumed by many downstream communities for household agriculture, potable and fishing purposes. Today city’s treated wastewater is pumped directly into the ocean. National Water Supply and Drainage Board (NWSDB) is the responsible party for the disposal, and they did this through two ocean outfalls North & South of Colombo (Jayakody et al., 2006).

When considering industrial wastewater generation, the Textile industry is one of the significant wastewater generators and releases more pollutants that may affect the environment and human health. It utilizes a large quantity of water and a large volume of wastewater generated from different production processes. The textile sector is essential because of its contribution to economic activity and employment. About 16% of the country's Gross Domestic Product (GDP) comes from the textile industry, and it enhanced by 8.52% in 2014 compared to 7.8% in 2013 (Figure 2-1). The textile industry has accounted for 40% of total exports and 52% of industrial exports and provided more than 300,000 employment opportunities (Embuldeniya, 2018).

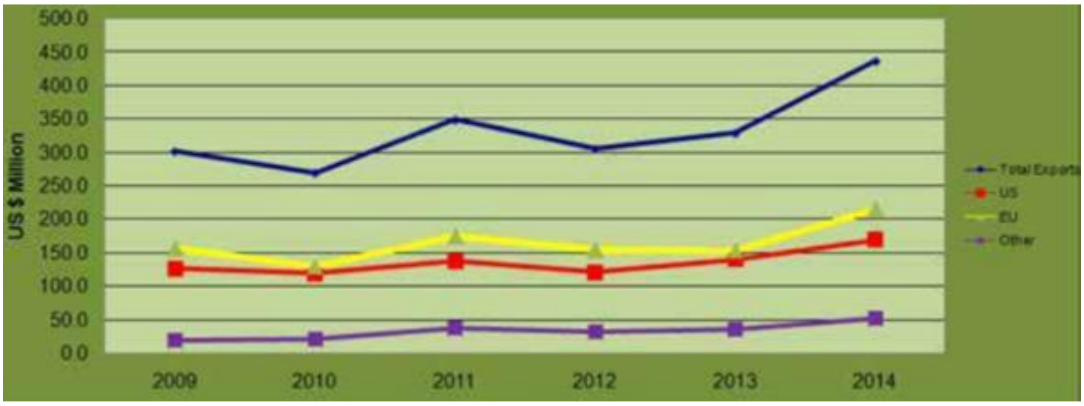

Figure 2-1: Export earnings from 2009 – 2014 [Source: (Embuldeniya, 2018)]

Although the textile industry has many economic benefits, the effluent from the textile plants across the country has been an environmental challenge. Handling wastewater that contains chemicals such as acids, alkalis, dyes, hydrogen peroxide, starch, surfactants dispersing agents, toxic metals, and solid waste has been a critical challenge in the last decade (Paulo et al., 2013). However, around 10% of wastewater is discharged into the environment without treatment by some industries (CEA, 2008). CEA stated that many small-scale manufacturers operating without formal licenses are responsible for untreated wastewater discharge. At the same time, large-scale industries move to treat their effluent, obtain international standards and local standards, and gain sustainable development. Therefore, CEA and other relevant authorities (Board of Investments) seek further wastewater treatment beyond the typical secondary wastewater treatment methods.

The wastewater from printing and dyeing units is often rich in colour, containing reactive and acid dye residues. Due to this, dyes cause to increase in Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and Total Dissolved Solids (TDS). The dyes used for the process contain aromatic and heterocyclic compounds, with colour-display groups and polar groups resulting in incredible difficulty in degrading the printing and dyeing wastewater. As a developing country, building individual wastewater treatment plants at the city level is impossible in Sri Lanka. The NWSDB maintains a small number of treatment plants at Ratmalana and Ja-Ela; however, they lack the potential to treat large quantities of industrial wastewater. The Central Environmental Authority (CEA) stated that major industrial parks generate 30 million cubic meters of wastewater per year, and Biyagama, Seethawaka, Horona, and Greater Colombo - 1st phase has a treatment capacity of 7.5, 9, 11, and 2.5 million cubic meters of wastewater per year, respectively. Treated wastewater from treatment plants is discharged into nearby natural waterways that provide water for agriculture and other uses.

2.5. Constructed wetlands for wastewater treatment

There are several methods for treating wastewater based on its quality and quantity. Moreover, have to consider treated wastewater discharge points and reuse. According to (Cheremisinoff, 2001), there are three main areas: Physical, chemical, and energy-intensive methods. Therefore, selecting a wastewater treatment system should be based on more than just technical knowledge; it should also consider human and environmental aspects. Wastewater treatment can be approached through several methods. Pre-treatment, Secondary treatment, and tertiary treatment were mainly identified. Solid waste, grease, oil, sand, and large particles are screened out ensuing treatment using physical filtration and sedimentation processes. BOD will reduce by 20% - 30% in primary treatment, and TSS will reduce by 50% - 60% by removing larger particles.

The secondary treatment method is a biological process that removes the dissolved organic particles that outflow primary treatment by microorganisms. In secondary treatment process may remove up to 85% of suspended particles and achieve lower

BOD levels (Cheremisinoff, 2001). Tertiary treatment is an additional treatment beyond secondary. The primary purpose of the treatment is effluent polishing before being discharged or reused. The tertiary treatment process includes membrane filtration (micro, nano, ultra, reverse osmosis), infiltration/percolation, activated carbon, and disinfection (chlorination, ozone, and UV). Tertiary treatment-related technology can be costly, requiring advanced technical knowledge, training personnel, energy supply, and chemicals. However, this tertiary treatment is rarely employed in low-income countries. Therefore, focusing on ecological technologies is more prioritized in the wastewater treatment process than high-engineering technologies nowadays. CW is an innovative and emerging ecological technology for environmental safety and restoration and a suitable solution for developing countries that seek low-cost and sustainable wastewater treatment systems (Babatunde et al., 2008; Vymazal, 2011)(Babatunde et al., 2008; Vymazal, 2011).

CWs have become a popular option for wastewater treatment in recent decades, and they have been acknowledged as compelling alternatives to traditional wastewater treatment technologies. This is due to its excellent effectiveness in removing pollutants, ease of operation and maintenance, minimal energy requirements, high rates of water recycling, and ability to provide significant animal habitat (Kadlec & Wallace, 2008; Vymazal, 2011). CWs have traditionally been used to treat domestic sewage in developing countries, and now CWs are gradually being used to treat other types of wastewater such as industrial wastewater, agricultural wastewater, sludge effluent, oil-produced wastewater, stormwater runoff, sugar factory wastewater, hospital wastewater, laboratory wastewater, and landfill leachate. (Chen et al., 2009).

Many developing countries have tropical and subtropical warm temperatures and high humidity throughout the year. A warm environment encourages year-round plant growth and increases microbiological activity, improving treatment efficiency (Kaseva, 2004; Zhang et al., 2014). According to (Truu et al., 2009), tropical climates can help remove pollutants because bacteria residing in CWs are most active at temperatures between 15 and 25 degrees Celsius. The temperature has an impact on TKN and ammonium removal efficiency. Nitrogen removal rates are substantially higher at water temperatures over 15°C (Casellesosorio & Garcia, 2007). With each 10 °C increase in temperature from 0°C to 30°C, ammonia volatilization increases 1.3–3.5 times, while denitrification rates double (J. Ng & Gunaratne, 2011). Therefore, CWs are a more suitable treatment process for the developing countries in the tropics and subtropics. High rainfall and perennial watercourses build cities close to any water body when considering the Sri Lankan condition. As such, treated water may discharge into a sensitive area or water body which may entangle with a sensitive area.

CWs technology to treat various sorts of wastewater is effectively utilized for decades to treat many forms of wastewater using a complicated mixture of plants, substrate, water, and microorganisms. CWs technology based on phytoremediation could be a cost-effective and environmentally friendly option (Babatunde et al., 2008; Langergraber et al., 2009; Ockenden et al., 2012; Rai et al., 2013). Biological activities are found to be acting higher in CW technology when compared with the conventional treatment systems, thereby various pollutants are converted into non-toxic by-products in the wastewater (Almuktar et al., 2018; Kadlec & Wallace, 2008). The performance of a CW system is based on the nature, design, local weather conditions, microbial activities, and the selected plant types (Bulc & Ojstršek, 2008; Mbuligwe, 2005).

As the term suggests, constructed wetlands are artificial wetlands that do not occur naturally. There are different types of constructed wetlands to serve different purposes;

- to conserve native flora and fauna, including aquatic plants, fish, water birds, reptiles, amphibians, and invertebrates which are threatened due to agricultural and urban development,
- to control floods,
- to be used for the production of food and fibre, and
- to treat wastewater

Constructed wetlands are efficient, low-cost, and sustainable systems for wastewater treatment consisting of shallow ponds or channels planted with aquatic plants. The CW is designed according to the natural wetland concept such that the process of natural wetland can be achieved under a controlled environment (Vymazal, 2010). A CW is a combination of a wetland basin, inlet, outlet, substrate, and vegetation

(Babatunde et al., 2008). The vegetation of the CW is the major element, and it enhances the visual characteristics of the system (Kalff, 2002). These plant species are the major source of biological, chemical, and physical interactions; hence, the wastewater is purified (Leto et al., 2013).

The types of plants are carefully chosen to treat the microbial, biological, physical, and chemical quality of wastewater (EPA, 2000; Vymazal, 2011). Typically constructed wetlands are used for urban and domestic wastewater treatment (Brix et al., 2011; El Hamouri et al., 2007). At present, constructed wetlands have been applied to the treatment of agricultural wastewater, industrial dairy wastewater, industrial tannery wastewater, industrial textile wastewater, pulp and paper industry wastewater, and acid mine drainage wastewater (Vymazal, 2007, 2011).

Over the last two decades, the applications for industrial wastewater treatment have increased with the evolution of technology and comprehensive research in the field (Calheiros et al., 2015). CWs are intended to gain naturally occurring processes involving wetland vegetation, soils, and associated microbial assemblages for environment clean-up (Kadlec & Wallace, 2008; Vymazal, 2007). Therefore, when we consider the advantages of constructed wetland treatments, they require low external energy input while achieving high levels of treatment with little or no maintenance.

2.6. History of constructed wetlands in Sri Lanka

Early Sri Lankan civilization followed a similar approach to today's phytoremediation. This technology was termed '*Kattakaduwa*', a distinct piece of land cultivated with various plant species to remove metals and salts from seepage connected to a tank cascade system. There are several other examples we can observe used by early society. '*Kohila kotuwa*' (*Lassia Spinosa*) coupled with bathing wells and the Owita system was another important application of Phyto-remediation in purifying the Owita system Phyto-remediation in purifying water after bathing and washing. '*Owita*' acted as a sand trap, preventing sedimentation and ensuring clean water flow (Bélair et al., 2014)

Additionally, (Bélair et al., 2014) indicated that the Thawulla of the ancient tank cascade system provides evidence for the constructed wetland function in ancient irrigation hydraulic systems in Sri Lanka. Although CW technology is not a new concept in Sri Lanka, it has received little research or industrial application attention. According to (Bélair et al., 2014), the CW study was completed in Sri Lanka, and the plant species and types of wastewater treated are associated characteristics.

2.7. Classification of Constructed wetlands

Constructed wetlands are engineered systems developed and built to treat wastewater by utilizing natural processes involving wetland vegetation, soils, and their associated microbial assemblages. They mimic many naturally occurring activities in wetlands but in a more controlled environment (Hammer & Bastian, 1989). The major characteristics of various types of CWs for wastewater treatment include vegetation type, the water level in relation to the surface, and the direction of flow (Vymazal, 2010). A horizontal flow type CWs can have submerged (water level keep above in relation to the surface), emergent (water level can keep either above or below in relation to the surface), free-floating (water level keep above in relation to the surface), and floating leaved (water level keep above in relation to the surface) vegetation. The CWs with the up or down vertical flow will consist of emergent-type vegetation while keeping the water level below the surface (Vymazal, 2010).

Several constructed wetlands are purposely built to achieve different purposes as depicted in Figure 2-4. Water flow regime (surface and subsurface) and type of aquatic plant development are two essential criteria for constructing wetlands. The CWs can be categorized according to their main design characteristics and process of pollution removal.

There are mainly two types when considering the water flow within the beds. Free water surface flow CW (FWSCW) and sub-surface flow CW. Sub-surface flow is divided into the vertical flow constructed wetland (VFCW), horizontal flow constructed wetland (HFCW), French vertical flow constructed wetland (FVFCW), and hybrid type CW (Vymazal, 2007).

Free water surface CWs can treat various types of wastewater, such as domestic wastewater and municipal wastewater (Kadlec & Wallace, 2008). Reed beds and gravel are used as a bed medium with a sloping bottom, providing a hydraulic gradient for subsurface flow treatment. The constructed wetlands have a long-term functioning capacity and remain stable for many years (Paulo et al., 2013).

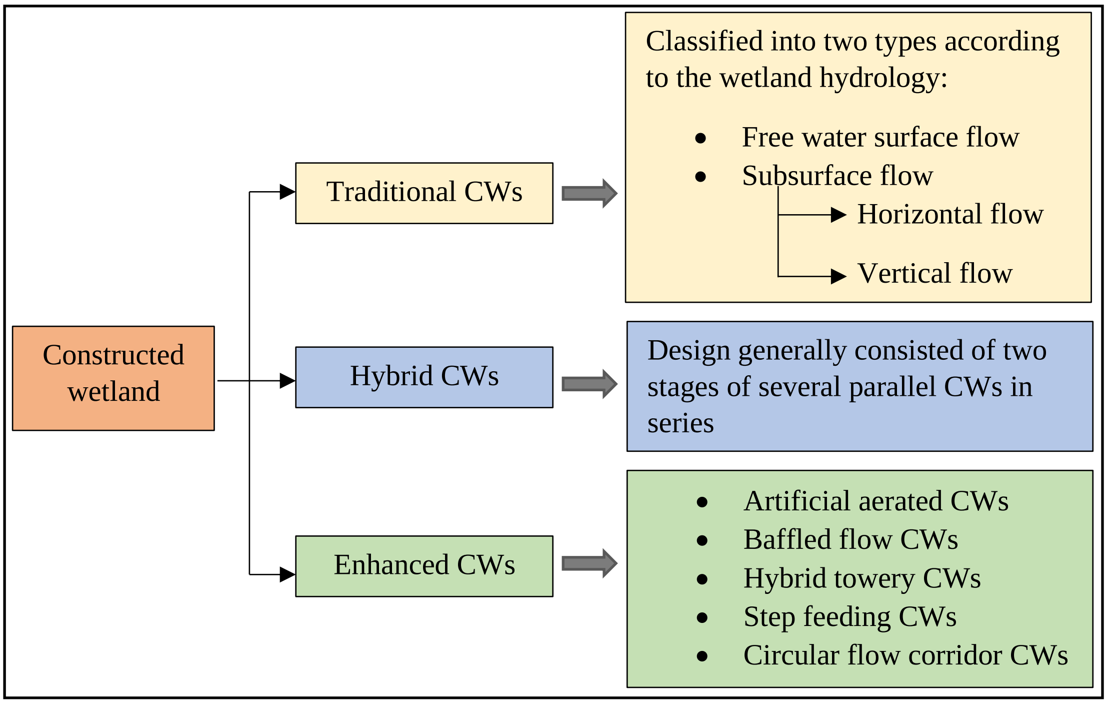

Figure 2-2: The classification of CWs used in wastewater treatments (Source:(Wu et al., 2015))

2.4.1. Free water surface flow constructed wetland

This is a natural wetland in which wastewater flows over the surface. This helps in flood prevention and shoreline erosion control while enhancing wastewater quality (Farooqi et al., 2007). In the FWSCW, a wide range of plants can be used, such as emergent plants (Typha, Phragmites, Scirpus) and submerged plants (Potamogeton, Elodea), and floating plants (Eichornia, Lemna) (Calheiros et al., 2015).

Free water surface constructed wetland has a mean removal efficiency for trace metals (Iron 53%, Copper 45%, Zinc 52%, and Lead 52%), BOD and COD (50% – 60%), TSS (70% – 80%), and Nitrogen (50% – 65%) (El-Sheikh et al., 2010). The research Vymazal, 2010 mentioned that the FWSFCWs are efficient in microbial degradation; hence, organics can be removed. The dense vegetation of the CW effectively removes the suspended solids through filtration and settling techniques. Nitrification and subsequent denitrification, and ammonia volatilization due to algal photosynthesis are the nitrogen removal mechanisms (Kadlec & Wallace, 2008; Vymazal, 2010). The effectiveness of Phosphorous removal is low because the wastewater and soil particles interaction time are low; hence the absorption/precipitation is limited (Kadlec & Wallace, 2008; Vymazal, 2010). The plant uptake is only temporal storage which in return is released to the system as a result of plant decay (Vymazal & Kröpfelová, 2008).

The FWSCWs are used for various types of wastewater worldwide. New Zealand, Australia, United Kingdom, Sweden, Germany, Spain, Kenya, Greece, Canada, and Norway has successfully implemented the FWSCWs for different types of wastewater (Bavor et al., 2001; Pontier et al., 2004; Thorén et al., 2004).

2.4.2. Horizontal flow constructed wetland

This system is known as a reed bed system. The wastewater flows horizontally in the bed of the constructed wetland (Vymazal, 2010). The wastewater undergoes both aerobic and anaerobic conditions. The organic matter is degraded by anaerobic and aerobic conditions around the root zone. The Horizontal Flow Constructed Wetland (HFCW) effectively removes BOD, COD, Ammoniacal Nitrogen, Phosphate, and TSS in the wastewater (Solano et al., 2004; Steer et al., 2005). Hence, it can treat different types of wastewater (i.e., industrial waste, agricultural waste, and mine waste). Whether a Horizontal Flow Constructed Wetland requires more land area than a vertical flow-constructed wetland, it has more efficiency in denitrification (Calheiros et al., 2015; Knight et al., 2000; Saeed & Sun, 2012; Sudarsan et al., 2018). Ammonia removal is limited because of the permanent waterlogged condition. Ligand exchange is the primary mechanism of Phosphorous removal which is comparatively low in HFCWs.

The HFCWs are successfully implemented in treating wastewater from the textile industry in Australia (T. H. Davies & Cottingham, 1994)

2.4.3. Vertical flow constructed wetland

In a vertical flow constructed wetland system, wastewater is submerged and discharged underneath, allowing wastewater to flow vertically. In a vertical flow constructed wetland system, the aerobic condition assists high nitrification and removes BOD, COD, and other pollutants. When comparing the land area, the requirement is less than the HFCWs but needs more maintenance because the system consists of pumps to pump wastewater on the wetland surface (Vymazal, 2010). The Phosphorous removal efficiency also can be increased by using a media with high sorption capacity.

2.4.4. French vertical flow constructed wetland

Two-stage vertical floe constructed wetland placed parallelly facilitating a series of functions. It has similar removal efficiency to vertical flow constructed wetlands and saves construction costs.

2.4.5. Hybrid constructed wetland

A hybrid-constructed wetland is a system combination of HWCW and VFCW. Compared with other types of constructed wetlands, a hybrid constructed wetland has more removal efficiency. Hybrid-constructed wetland units can be designed according to the characteristics of the wastewater (Barbera et al., 2009; Saeed & Sun, 2012; Yazdani & Alizadeh Golestani, 2019). Hybrid CWs are mostly used for the removal of ammonia-N and TKN (Vymazal & Kröpfelová, 2008).

2.4.6. Baffled sub-surface flow constructed wetland

This consists of a vertical baffle alongside the width of the wetland, which leads the wastewater to flow up and down through the wetland bed. This system allows more contact time between the wastewater and the media. Nitrogen removal can be achieved in the baffled sub-surface flow constructed wetland.

2.4.7. Aerated constructed wetland

For oxygen requirements, an aerated constructed wetland is an advanced option. It needs less energy than conventional treatment. The efficiency of constructed wetland is improved by using aerators in the wetland to avoid the low decomposing rate of organic matter arising from oxygen concentration (Sánchez-Monedero et al., 2008)

2.4.8. Multi-tropic free-flow engineered constructed wetland

In this constructed wetland, floating aquatic plants grow in wastewater, such as *Eichhornia crassipes,* and *Lemna spp.* etc. If floating plants have high efficiency in removing Nitrogen and Phosphates but have a low removal rate of BOD and COD. Regular harvesting is required to maintain the efficiency of the constructed wetland. Floating aquatic plants produces higher biomass which can be further used as a fuel, fertilizer, and animal feed supplement (Tilak et al., 2016).

2.8. Different levels of efficiency in constructed wetlands

Traditionally, CWs are designed as FWSCW and SSFCW. The pollutant removal mechanisms, which govern the treatment process and resulting performance of CWs, are different from form to form (Ilyas & van Hullebusch, 2020). Therefore, different types of CWs have different capacities for removal efficiencies. The most suitable CWs can be selected according to the wastewater characteristic. Several studies have been done on difficult wastewater types in past decades to understand the efficiency levels. Previous research studies for urban wastewater treatment showed that different CWs have different removal efficiencies such that attention should be paid when selecting the most suitable CW type (Hijosa-Valsero et al., 2012).

The floating macrophytes surface flow, free-water surface flow, and free-water subsurface flow showed the highest efficiency level for removal of COD; phragmites spp. The planted surface flow showed a high-efficiency level of BOD_5 removal;

Phragmites spp. Planted systems showed the highest capacity for eliminating TKN and NH_4-N.

It is known that the Physico-chemical parameters of CW are subject to spatial and temporal variations (Imfeld et al., 2009) even on a monthly or daily scale (Wießner et al., 2005). Excessive precipitation during the rainy season can substantially alter water levels in constructed wetlands, resulting in pollutant dilution and water chemistry changes (Katsenovich et al., 2009). However, root zone interactions with soil determine how effective CWs are at removing pollutants from wastewater (Zhang et al., 2014).

Among those constructed wetlands, tertiary treatment using FWSCW has recently become more common as a polishing step for treated effluent from traditional wastewater treatment plants (Toet et al., 2005). More than 70% removal efficiencies for TSS, COD, BOD, and pathogens can be attained in FWSCWs (Kadlec & Wallace, 2008). Nitrogen removal effectiveness is between 40% and 50%, and FWSCWs provide lone-term phosphorus removal at modest rates ranging from 40% to 90% (Vymazal, 2007).

2.9. Design and operation of the constructed wetland

The combination process of physical, chemical, and biological which occurs within the CWs leads to the removal of different types of pollutants. This removal efficiency may depend on the system design. For the design of the constructed wetland, location, type of flora, substrate type, construction material, wastewater type, hydraulic loading rate (HLR), hydraulic retention time (HRT), water depth, operation mood, and maintenance procedures are considered (C. Akratos et al., 2009; Kadlec & Wallace, 2008). However, hydraulics and pollution removal are two critical characteristics in the description of treatment wetlands.

2.6.1. Vegetation used in constructed wetland

Vegetation is an essential component of the design of CW treatments. When selecting plant species for a wetland, tolerance to waterlogged-anoxic and hyper-eutrophic conditions and pollution absorption capacity are suggested to adapt to harsh climates. Wetland vegetation helps to reduce carbon dioxide concentration and indirectly provides green space and a habitat area for the fauna (Sundaravadivel & Vigneswaran, 2001). In constructed wetlands, only a few plant species have widely used. The most commonly used emergent species are *Phragmites spp.* (Poaceae), *Typha spp.* (Typhaceae), *Scirpus spp.* (Cyperaceae), *Iris spp.* (Iridaceae), *Juncus spp.* (Juncaceae), and *Eleocharis spp.* (Spikerush) (Vymazal, 2013). The most frequently used submerged plants are *Hydrilla verticillata, Ceratophyllum demersum, Vallisneria natans, Myriophyllum verticillatum,* and *Potamogeton crispus.* Frequently used floating leaved plants are *Nymphaea tetragona, Nymphoides peltata, Trapa bispinosa,* and *Marsilea quadrifolia.* The free-floating plants are *Eichhornia crassipes, Salvinia natans, Hydrocharis dubia,* and *Lemna minor.*

When considering the tolerance limit of the vegetation, it has to suffer from environmental stresses and extreme conditions of wastewater (Surrency, 2020). It might affect to limit both plant survivorship and treatment potential. There are various studies evaluating the ability of tolerance to contaminant levels of different wastewater (Gulf of Mexico Program et al., 1997).

Constructed wetland plants act as intermedium for purification reactions by enhancing various removal processes and directly utilizing Nitrogen, Phosphorous, and other nutrients. Moreover, they can accumulate heavy metals and antibiotics in wastewater (Liu et al., 2011). Plant uptake capacity mainly depends on system configurations, retention times, loading rates, wastewater types, and climatic conditions (Saeed & Sun, 2012).

2.6.1.1.Vegetative cover - *Phragmites karka*

Phragmites karka is a rapidly growing emergent aquatic weed and it is a marshy plant. Due to the rapid growth of this use of *Phragmites karka* can be introduced as a sustainable use in wastewater treatment. A research study has found that the CW with *Phragmites karka* has the ability to treat dark blackish and odorous wastewater to clean and odorless effluent (Dhulap & Chavan, 2012). The *Phragmites* plants perform several important functions in the CW systems, that enhance the effectiveness and efficiency of the CW performance. The *Phragmites* plants can feed the heterotrophic microorganisms with the supply of Oxygen in the rhizospheres (DeMaeseneer, 1982; Maeseneer, 1997). In addition, the hydraulic conductivity of the soil also increases when *Phragmites* plants are utilized in the CW. This was found in the research study conducted by Maeseneer, 1982. He has proved that the penetration of roots and rhizomes through the soil can crate voids within the soil particles; hence increasing the porosity of the media (Kickuth, 1980). The hydraulic conductivity of the rhizosphere is stabilized by the micropores regardless of the soil environment with the presence of *Phragmites* plants. This performance is equivalent to coarse sand performance.

The research study carried out by Dhulap & Chavan, 2012, found that 61.64% of TS removal, 60.37% of TDS removal, 63.19% of TSS removal, 57.15% of hardness removal, 94.69% of nitrate removal, 92.95% of Phosphate removal, 61.47% of BOD removal, and 64.74% of COD removal with the presence of *Phragmites* plants.

The root zone of *Phragmites karka* is an efficient and effective plant in the concept of CW in terms of removing solids, COD, organic and inorganic materials, and several other physicochemical parameters (Dhulap & Chavan, 2012).

2.6.2. Substrate selection

The substrate is the critical design parameter since it facilitates the wastewater flow within the wetland and provides a suitable growing medium for the plant (Kadlec & Wallace, 2008). Besides, substrate sorption may play the most crucial role in absorbing Phosphorous (Ji et al., 2022). When selecting the substrate of the constructed wetland, hydraulic conductivity and the capacity of pollutant absorption are considered. The hydraulic conductivity of the substrate is a significant factor in constructed wetlands. Poor hydraulic conductivity severely decreases the effectiveness of the system. As indicated in Table 2-1, different media consist of different hydraulic conductivity.

Table 2-2: Media characteristics (Chen et al., 2009)

Media type	Effective size (D_{10}) mm	Porosity (η)	Hydraulic conductivity (k_s) ms^{-1}
Coarse sand	2	0.32	1.2×10^{-2}
Gravelly sand	8	0.35	5.8×10^{-2}
Fine gravel	16	0.38	8.7×10^{-2}
Medium gravel	32	0.4	11.6×10^{-2}
Coarse rock	128	0.45	115.7×10^{-2}

Low adsorption affects the long-term removal performance of constructed wetlands (L. Wang et al., 2010).

The frequently used substrate materials are gravel, sand, clay, calcite, marble, vermiculite, slag, fly ash, bentonite, dolomite, limestone, shell, zeolite, wollastonite, activated carbon, and lightweight aggregates. They can be divided mainly into natural materials, artificial media, and industrial by-products (Albuquerque et al., 2009; Chong et al., 2013; Saeed & Sun, 2012; Yan & Xu, 2014).

The pollutant removal mechanism of the substrate from wastewater happens from the exchange, adsorption, precipitation, and complexation. The adsorption capacities of substrates differ from one another, and their capacity of sorption may depend primarily on the contents of the substrate. Furthermore, it could be influenced by hydraulic and pollutant loading.

The interlinks of mechanisms of the substrate in CWs are important for the performance and sustainability of the CWs. The functions which significantly influence the performance of wastewater include filtration function, adsorption function, electron donor function, plant support function, and microorganism carrier function.

The substrates can be classified into five categories; 1. Traditional mineral materials, 2. Chemical products, 3. Biomass materials, 4. Industrial and municipal waste materials, 5. Modified functional materials, and novel materials (Ji et al., 2022; H. Wang et al., 2018). Quartz sand, gravel, zeolite, and volcanic can be used as natural mineral materials. Chemical products of the substrate of CWs include ceramite, polystyrene foam, industrial zeolite, and composite substrate. Biomass materials used for CW substrate includes biochar, oyster shell, rice straw, and reed. Slag, drinking water treatment residual, broken brick, and sawdust are the industrial and municipal by-products used in CW substrates. Modified functional materials include modified ceramite, biological ceramite, thermally modified attapulgite, and modified zeolite. Novel materials used as CW substrates include porous geopolymer, geopolymer-zeolite composite, light-expanded clay aggregate, and polysiloxane/micro-sized alumina (Ji et al., 2022).

2.6.3. Hydraulic load and retention time

When considering the controlling factors of the wetland, hydrology is one of the primary factors, and the flowrate should also be regulated to achieve a satisfactory treatment performance (C. Lee et al., 2009). Hydraulic Loading Rate (HLR) and Hydraulic Retention Time (HRT) play an essential role in the removal efficiency of constructed wetlands. A high hydraulic loading rate stimulates faster movement of the wastewater through the media, reducing the optimum contact time. A low HRT leads to incomplete denitrification of wastewater, and it is reported that nitrogen removal requires a longer HRT compared with that required for the removal of organics (C. Lee et al., 2009). Furthermore, HRT depends on the Vegetation of the constructed wetland, and it differs between constructed wetlands. An appropriate microbial community may be established in appropriate HRT and have adequate contact time to remove contaminants (Saeed & Sun, 2012; Yan & Xu, 2014).

2.6.4. Water column (in and above the substrate)

It is essential to maintain a water column due to its governing factor for ecological functioning occurring in the system. Water provides the environment for biochemical reactions and acts as a transport medium to carry the end-products, such as gases, and organic acids, from one reaction site to another (Sundaravadivel & Vigneswaran, 2001). In a constructed wetland system water is the mode of transport for delivering the pollutants as the influent and discharging the clear content as the effluent. The plan area of a CW is fairly large; hence, the depth of water is shallow. Therefore, the interaction with the atmosphere is significant. The density of the vegetative cover strongly acts to the changes in wetland hydrology (Omondi et al., 2020).

3. OBJECTIVES

The primary objective of the study is to evaluate the possibility of recommending a constructed wetland for the textile industry as a polishing step of wastewater treatment.

The following secondary objectives were identified for the research study.

- To observe the removal efficiencies of selected plantation and substrate at the different discharges.

  Different types of plantations and substrates can remove different types of contaminants in wastewater. The efficiency of the selected plantation and substrate in terms of contaminant removal will be assessed. Necessary practical measurements will be collected, and removal efficiencies will be determined.

- To evaluate the performance of constructed wetlands as a tertiary wastewater treatment method.

  The characteristics of wastewater discharged from the textile industry will be checked. The treated wastewater quality after the tertiary wastewater treatment (constructed wetland) will be assessed against the guidelines stipulated by respective authorities to ensure that the disposal of the treated wastewater does not release any contaminant into soil or water.

- To recommend a solution for improving the efficiency of constructed wetlands in Sri Lanka.

  The improvements to enhance the treated quality of the wastewater will be proposed based on the study.

4. METHODOLOGY

This chapter explains the methodologies adopted to achieve the specific objectives as set out in Chapter 1.

The flowchart of the research methodology is depicted in Figure 4-1.

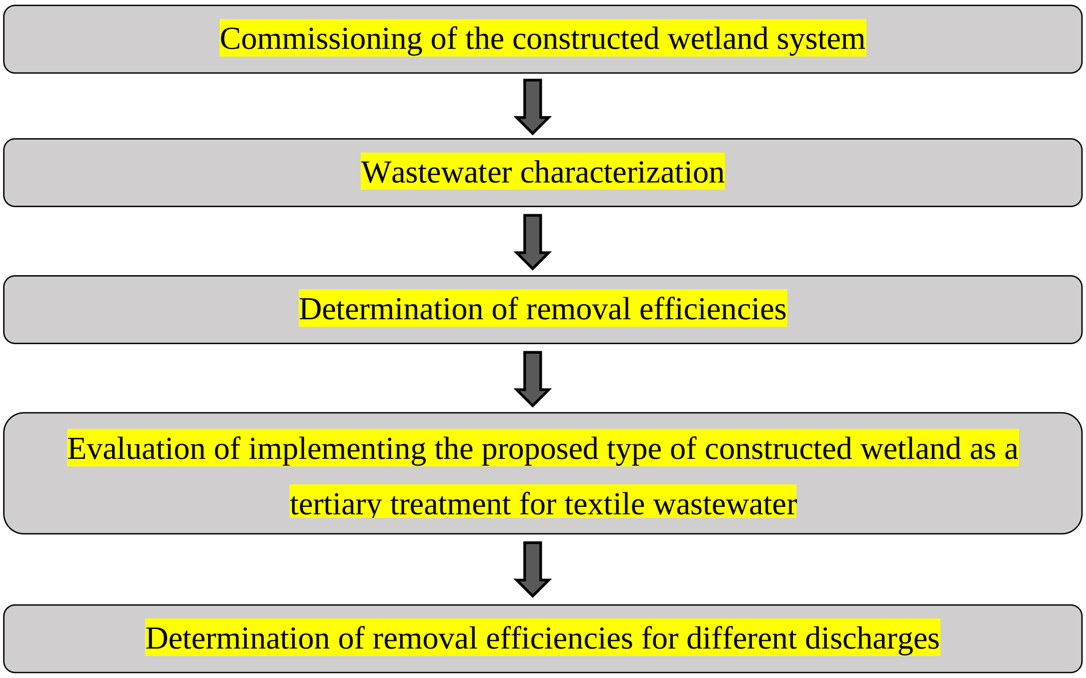

Figure 4-1: Flow chart of the research methodology

4.1. Commissioning of the constructed wetland system

4.1.1. Data collection

The wastewater samples were collected from the pre-determined locations (Figure 4-2); A. Near the inlet of the initial treatment zone of the constructed wetland (Figure 4-3), B. In the middle of the constructed wetland (Figure 4-4), C. Near the outlet of the final treatment zone of the constructed wetland (Figure 4-5), and D. Before discharging to the surface water canal (Figure 4-6).

The collected wastewater samples were analyzed for various physio-chemical properties as depicted in Table 4-1. The physio-chemical properties include pH, temperature, colour, BOD, COD, TSS, Total Kjeldahl Nitrogen (TKN), dissolved phosphates, faecal coliform. The pH and temperature will be checked daily at the in-house laboratory of Naturub Group of Companies. Another set of samples will be collected and then transported to Environmental Engineering Laboratory, the University of Moratuwa to check the other water quality parameters.

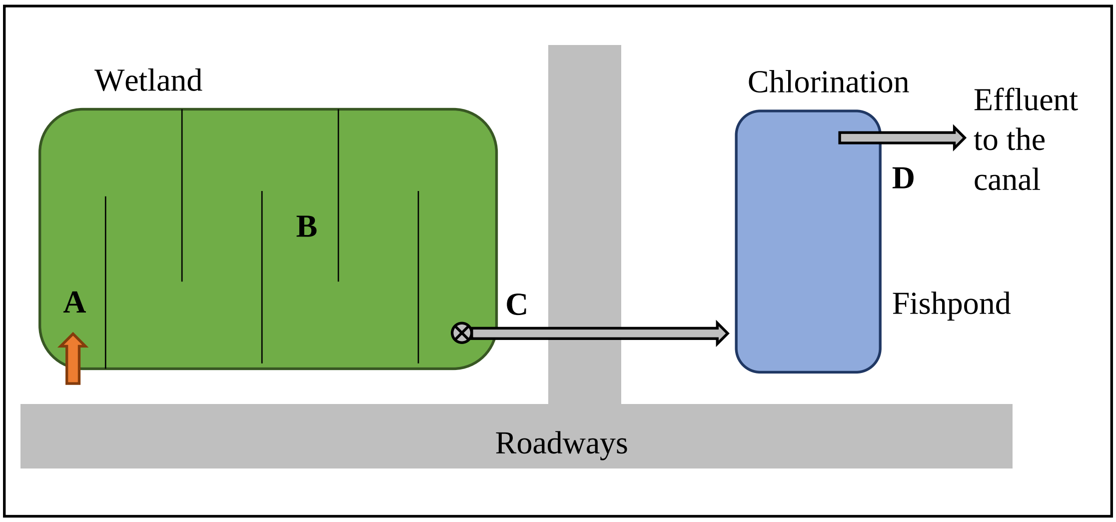

Figure 4-2: Schematic diagram of sampling points

Figure 4-3: Location A - Near the inlet of the initial treatment zone of the constructed wetland

Figure 4-4: Location B - In the middle of the constructed wetland

Figure 4-5: Location C - Near the outlet of the final treatment zone of the constructed wetland – water was collected through a bypass

Figure 4-6: Location D - Before discharging to the surface water canal

Table 4-1: Sampling frequency of the samples

	Parameters	Sampling frequency	
		Daily	**Weekly**
1	pH	√	-
2	Temperature	√	-
4	BOD	-	√
5	COD	√	-
6	TSS	√	-
7	TKN	-	√
8	Dissolved Phosphate	-	√
9	Faecal Coliform	-	√
9	Faecal Coliform	-	√

4.1.2. Wastewater characterization

The set of sample bottles was stored according to the standards to be followed. The bottles were refrigerated at 4 °C until analysis. In-situ measurements were obtained for pH and temperature. Other parameters were tested as ex-situ parameters. Samples were collected in bottles (500 ml each) for determination of TSS, dissolved phosphate, and TKN, and separate 50 ml samples were for determination of COD. The samples collected to determine dissolved phosphate were filtered in-situ using a 10 ml syringe and a disposable glass fibre filter of mesh size 0.45 µm. The experiments were carried out for 3 hours for TSS. The collected samples were preserved with concentrated sulfuric acid of 0.5 ml/100ml and experiments were carried out by the next day. The procedures followed in determining the wastewater characteristics were as follows;

1. pH was measured using a portable multimeter (HI-9813, HANNA). The probe was dropped to the sub-samples and readings were obtained Appendix 4-1,
2. The temperature was measured using a portable multimeter (HI-9813, HANNA). The probe was dropped to the sub-samples and readings were obtained Appendix 4-1,
3. BOD was determined following the APHA 5210 B method. The detailed procedure was given in Appendix 4-2,
4. COD was determined following the APHA 5220 D method. The detailed procedure was given in Appendix 4-3,
5. TSS was determined following the APHA 2540 F method. The detailed procedure was given in Appendix 4-4,
6. Phosphate as Phosphorous was determined following the APHA 4500 P E method. The detailed procedure was given in Appendix 4-5,
7. TKN was determined following the macro Kjeldahl procedure (APHA 4500-Norg B) method. The detailed procedure was given in Appendix 4-6, and
8. Faecal Coliform was determined following the most probable number method (MPN index/100 mL of pathogenic indicators). The detailed procedure was given in Appendix 4-7.

4.1.3. Determination of removal efficiencies

The performance of the constructed wetland was assessed in terms of the removal efficiency of collected physio-chemical parameters. The removal efficiency was calculated using Equation 4-1.

Equation 4-1: Removal Efficiency

$$Removal\ Efficiency = \frac{In-Out}{In} \times 100\ \%$$

Where:

In = Inlet concentration (mg/L)

Out = Outlet concentration (mg/L)

4.1.4. Evaluation of implementing the proposed type of constructed wetland as a tertiary treatment for textile wastewater

The previously determined efficiencies were assessed in terms of different discharges, for the selected vegetation and substrate. Based on the results the necessity of a constructed wetland as a tertiary treatment for textile wastewater was evaluated.

5. RESULTS

5.1. Selection of the location for the constructed wetland and fishpond

A marshy area neighboring the canal has been selected to construct and implement the constructed wetland. The land extent is 2 acres and is dilapidated land. The area was previously used for paddy cultivation. The land is covered with ‘Wel Atha’ plants. A peat soil condition is observed. The proposed land is situated in the flood plain of the canal; hence it goes under water easily during the wet season. The photographic observation of the proposed constructed wetland is depicted in Figure 5-1.

Figure 5-1: Photographic observations of the constructed wetland and the fishpond. A: Constructed wetland, B: Fishpond, C: Existing WWTP

5.2. Treatment performance of constructed wetland system

The removal efficiency (%) of the constructed wetland system at different flow discharges were given in Table 5-1.

Table 5-1: Removal efficiency (%) of the constructed wetland system for different flow discharges

	Parameters	Removal efficiency (%) in different flow discharges				
		20%	40%	60%	80%	100%
1	COD	23.9	78.6	83.4	75.8	72.3
2	BOD	18.5	68.1	72.9	47.7	51.8
3	TSS	27.8	46.3	50.3	58.4	47.2
4	Nitrogen	-0.4	65.5	42.9	N/A	N/A
5	TP	66.7	75.0	77.8	N/A	N/A

N/A: Not Applicable

The expected removal efficiencies as per the initial proposal were depicted in Table 5-2 with the observed efficiency after the implementation of constructed wetland with 100% of the discharge.

Table 5-2: Expected and observed removal efficiency (%) of the constructed wetland system

	Parameters	Expected efficiency (%)	Observed efficiency (%)
1	COD	45.0	72.3
2	BOD	16.7	51.8
3	TSS	15.0	47.2
4	TKN	Not reported	25
5	TP	Not reported	73
6	pH	Not reported	2.4
7	Temperature	Not reported	0

The removal efficiencies between the sample points were depicted in Table 5-3 for wastewater characteristics of COD, BOD, TSS, TKN, and TP.

Table 5-3: Removal efficiency (%) in between selected points

	Parameters	Removal efficiency (%) in between sample points		
		AB	BC	CD
1	COD	56.3	16.7	14.3
2	BOD	27.3	20.5	10.7
3	TSS	20.1	22.3	10.5
4	TKN	25	-33	13
5	TP	50	32	23

The vegetation cover observations at different sampling points were depicted in Table 5-4.

Table 5-4: Vegetation cover at the sample points

	Location	Observed vegetation cover
1	A to B	√√√
2	B to C	√√
3	C to D	√

Legend

√√√	Observed 80 – 90% *Phragmites* spp. density
√√	Observed 40 – 60% *Phragmites* spp. density
√	Could not observe *Phragmites* spp. density

5.3. Changes in selected parameters when influent flows through the wetland

5.3.1. Changes in COD

A reduction in COD was observed regardless of the discharge percentage (Figure 5-1). The average COD levels observed for 20% of the discharge at sample point A, B, C, and D was 45.7 mg/L, 23.6 mg/L, 22.7 mg/L, and 34.8 mg/L, respectively. As per the observations for 20% of the discharge, there is a reduction in COD levels from A to B and B to C and an increment in COD levels from C to D (Figure 5-1). The overall efficiency was around 23% when the discharge of 20% is considered. The expected efficiency for COD removal from the CW proposal was 45% whereas the requirement was not met for the discharge of 20%.

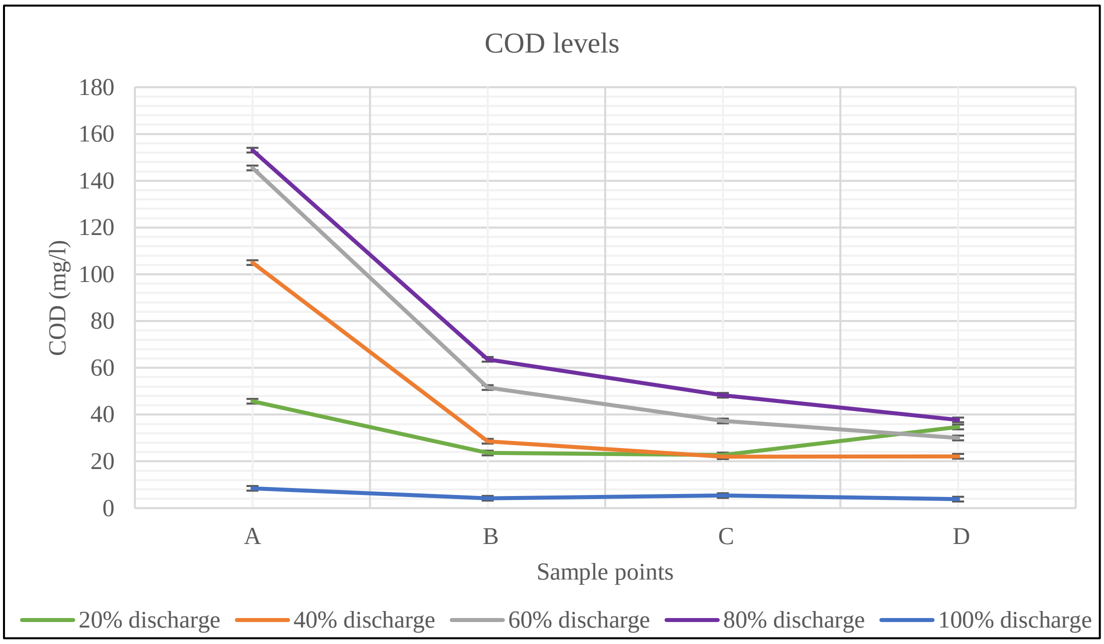

Figure 5-2: Changes in COD levels for different discharges

When the discharge was gradually increased up to 40%, the observed COD levels at sample points A, B, C, and D were 105 mg/L, 28.61 mg/L, 22.0 mg/L, and 22.2 mg/L, respectively. The COD level at sample point A in the discharge of 40% was higher than the COD level at sample point A in the discharge of 20%. The COD reduction pattern was similar for the discharge of 20% for each sample point (Figure 5-1). However, the increment of the COD level from sample point C to sample point D is negligible. The overall COD removal efficiency for the discharge of 40% is around 78% which is greater than the removal efficiency for the discharge of 20%. The expected COD removal efficiency was sufficiently reached when the discharge of 40% is considered.

In the third step, the discharge was increased up to 60%, and the observed COD levels at sample points A, B, C, and D were 141.4 mg/L, 50.1 mg/L, 36.2 mg/L, and 29.1 mg/L, respectively. A similar COD removal pattern was observed for sample points A, B, and C. For the discharge of 60%, further reduction in COD level from sample point C to D was observed whereas for discharge of 20% and 40% an increment in COD levels from sample point C to D was observed (Figure 5-1). The removal efficiency obtained was 83% for the discharge of 60% which met the design criteria.

The observed COD removal levels for 80% of the discharge at sample points A, B, C, and D were 153.1 mg/L, 63.6 mg/L, 48.3 mg/L, and 37.8 mg/L, respectively. A gradual decline of the COD levels was observed similar to the discharge of 60% (Figure 5-1). The removal efficiency was around 76% which is lower than the efficiency obtained for the discharge of 60%. However, 76% of the removal efficiency met the design criteria.

The average COD levels observed for discharge of 100% at sample points A, B, C, and D were160.5 mg/L, 64.0 mg/L, 52.6 mg/L, and 44.3 mg/L, respectively. A similar trend as the discharge of 80% in COD removal was observed for the discharge of 100% as well (Figure 5-1). The COD removal efficiency for discharge of 100% was around 72% which is a little less than the COD removal efficiency for discharge of 80%. However, the removal efficiency for discharge of 100% met the design criteria.

Although there is a reduction in removal efficiencies from the discharge of 60% to the discharge of 100%, the COD level at sample point D is acceptable as per the guidelines stipulated by the CEA; 250 mg/L for inland surface watercourses.

The average COD levels for discharge of 100% at each sampling point was depicted in Figure 5-2. As per the bar chart depicted in Figure 5-2, the COD removal rate was reduced from sample point A to sample point D. In addition, the predicted level of COD to the constructed wetland is around 160.5 mg/L with a standard deviation of 41 mg/L (Figure 5-2). An average COD level of 64.0 mg/L with a standard deviation of 4.2 mg/L can be predicted at sample point B (Figure 5-2). Similarly, the COD levels around 52.6 mg/L with a standard deviation of 5.4 mg/L and 44.3 mg/L with a standard deviation of 3.8 mg/L can be observed at sample points C and D, respectively (Figure 5-2).

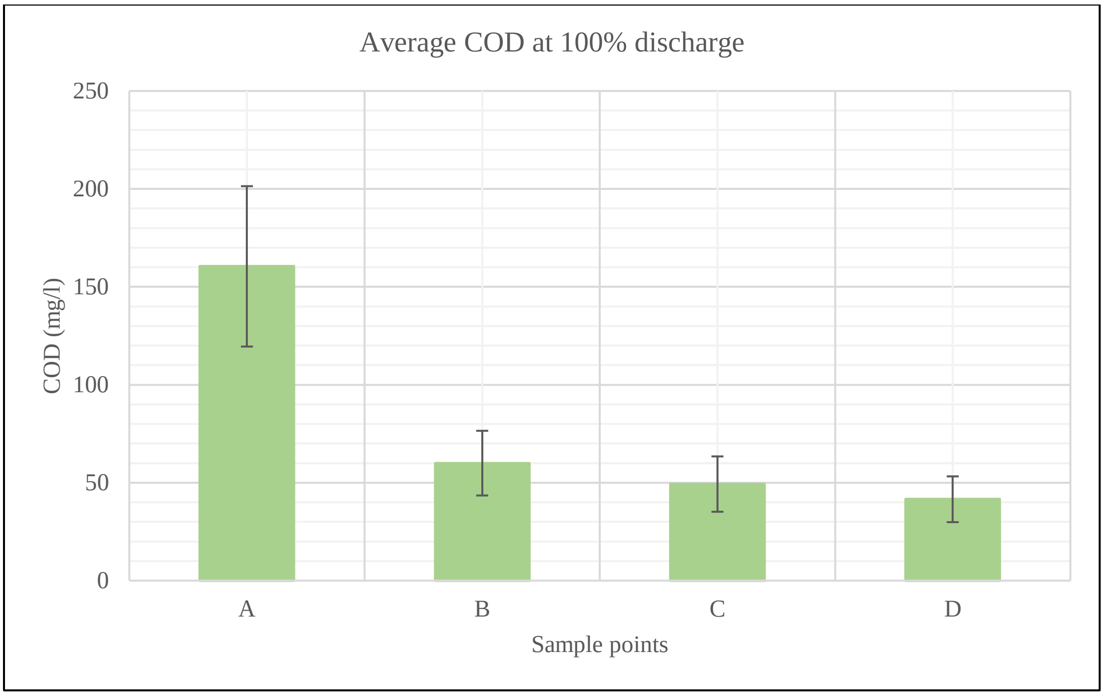

Figure 5-3: Average values of COD at each sampling point

5.3.2. Changes in BOD

A reduction in BOD was observed regardless of the discharge percentage (Figure 5-3). The average BOD levels observed for 20% of discharge at sample point A, B, C, and D was 27.3 mg/L, 15.6 mg/L, 15.4 mg/L, and 21.6 mg/L, respectively. As per the observations for 20% of the discharge, there was a reduction in BOD levels from A to B. The difference in BOD levels from B to C was negligible. There was an increment in BOD levels from C to D. The BOD removal efficiency when 20% of discharge is considered is about 27%. The expected efficiency for BOD removal from the CW proposal was 16.7% and the observed values for 20% of discharge also met the requirement.

The observed BOD levels at points A, B, C, and D, when 40% of discharge was considered were 47.4 mg/L, 14.9 mg/L, 12.4 mg/L, and 14.7 mg/L, respectively. The BOD levels at sample point A for different discharges showed the same pattern as COD levels at sample point A. With the increase in percentage discharge BOD level at point A increased and corresponded with the effluent values (Figure 5-3). The overall BOD removal efficiency for discharge of 40% was around 67%. The expected

COD removal efficiency was sufficiently reached when the discharge of 40% was considered.

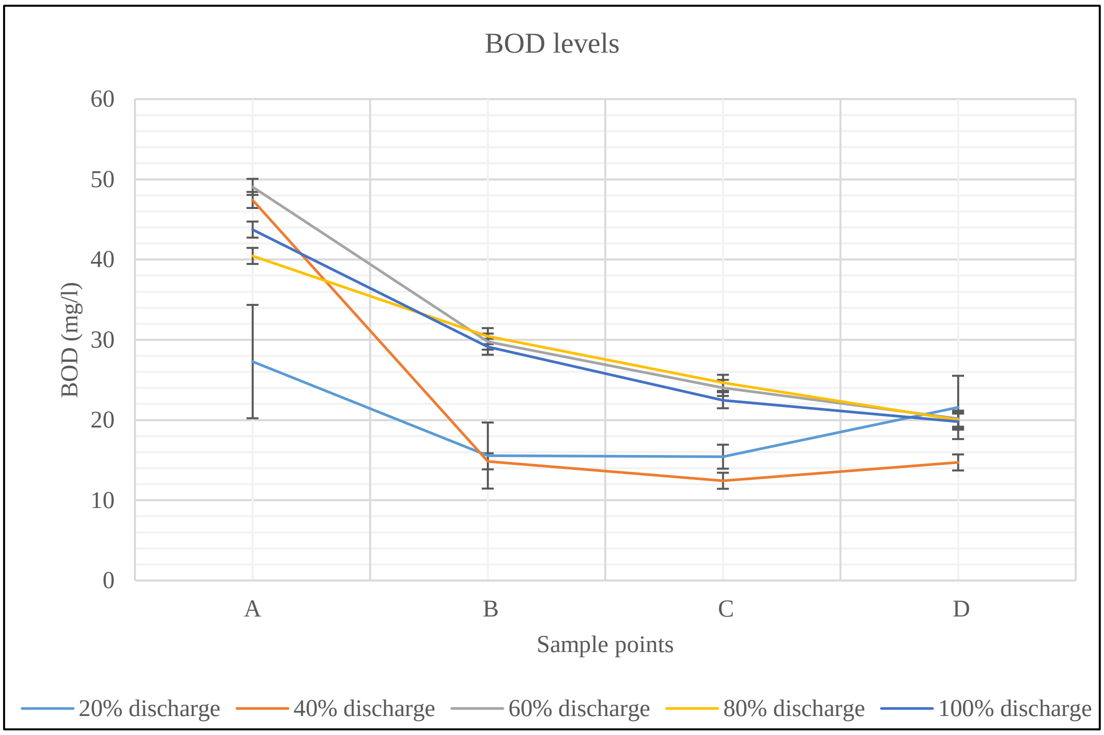

Figure 5-4: Changes in BOD levels for different discharges

Then the discharge was increased up to 60%, and the observed BOD levels at sample points A, B, C, and D were 49.1 mg/L, 29.8 mg/L, 24.0 mg/L, and 20.2 mg/L, respectively. A similar pattern was observed for BOD removal for points A, B, and C. For discharge of 60%, further reduction in BOD level was observed for point D as well. The removal efficiency was 72% for discharge of 60% which met the design criteria.

The observed BOD removal levels at sample points A, B, C, and D for 80% of the discharge were 40.5 mg/L, 30.5 mg/L, 24.6 mg/L, and 20.0 mg/L, respectively. The reduction pattern of BOD levels at the discharge of 80% was similar to the discharge of 60% (Figure 5-3). The removal efficiency for discharge of 80% was around 76% which met the design criteria.

The average BOD levels at sample points A, B, C, and D for the discharge of 43.7 mg/L, 29.1 mg/L, 22.5 mg/L, and 19.8 mg/L, respectively. The reduction pattern of

BOD levels at the discharge of 100% was similar to the discharge of 80% (Figure 5-3). The BOD removal efficiency for discharge of 100% was around 52%, which is less than the observed efficiency of 80%. However, the design requirement for BOD removal was reached even with this removal efficiency. Although the BOD removal efficiency was reduced to 52% at a discharge of 100%, the BOD level at sample point D was acceptable as per the guidelines stipulated by the CEA; 60 mg/L for inland surface watercourses.

The average BOD levels for discharge of 100% at each sampling point was depicted in Figure 5-4. As per the bar chart depicted in Figure 5-4, the BOD removal rate was reduced from sample point A to sample point D.

In addition, the predicted level of BOD in the constructed wetland was around 43.7 mg/L with a standard deviation of 13.1 mg/L (Figure 5-4). An average BOD levels at sample points B and C were 29.1 mg/L (standard deviation = 4.8 mg/L) and 22.5 mg/L (standard deviation = 3.0 mg/L), respectively. The average COD level at the outlet point (sample point D) was 19.8 mg/L (Figure 5-4).

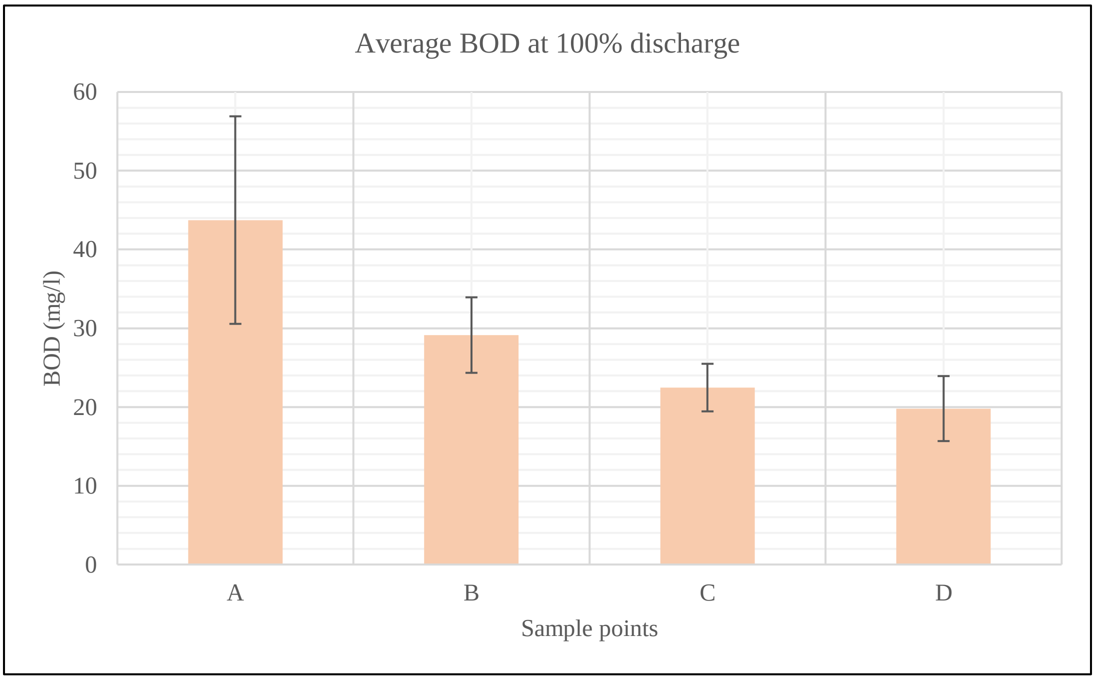

Figure 5-5: Average values of BOD at each sampling point

5.3.3. Changes in TSS

The TSS levels for different discharges at sample points A, B, C, and D were depicted in Figure 5-5. The TSS levels for discharge of 20% at sample points A, B, C, and D were 13.9 mg/L, 9.7 mg/L, 7.9 mg/L, and 10.0 mg/L, respectively (Figure 5-5). The average TSS removal efficiency was around 27% for discharge of 20%. The expected removal efficiency as per the design proposal was 15%; hence, the observed removal efficiency met the design proposal criteria. It was observed that the TSS levels were reduced from points A to C and increased at point D when the discharge of 20% was considered.

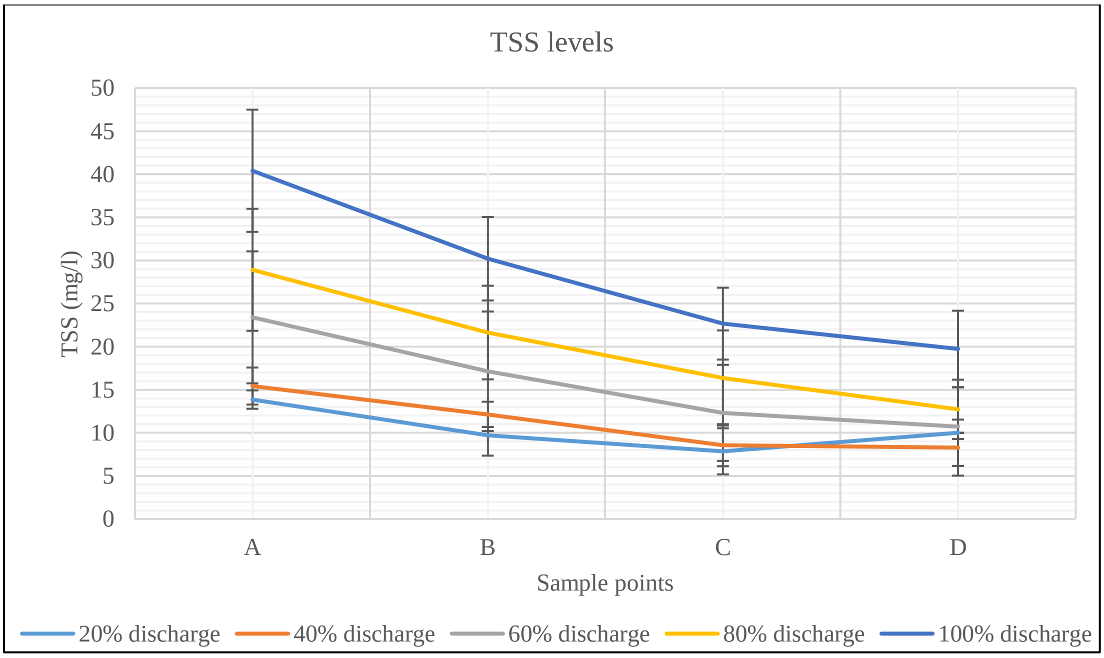

Figure 5-6: Changes in TSS levels for different discharges

The TSS levels for discharge of 40% at sample points A, B, C, and D were 15.4 mg/L, 12.1 mg/L, 8.6 mg/L, and 8.3 mg/L, respectively (Figure 5-5). The average TSS removal efficiency was around 49% for discharge of 40% which is higher than the TSS removal efficiency for discharge of 20%. A gradual reduction was observed in TSS level when the discharge of 40% was considered (Figure 5-5).

The observed TSS levels at sample points A, B, C, and D for discharge of 60% were 23.4 mg/L, 17.1 mg/L, 12.3 mg/L, and 10.7 mg/L, respectively (Figure 5-5). The observed TSS removal efficiency for discharge of 60% was 47% which was a little less than the removal efficiency for discharge of 40%. A continuous reduction in TSS was observed from points A to D for the discharge of 60%.

The TSS values observed for discharge of 80% at sample points were 28.9 mg/L, 21.6 mg/L, 16.4 mg/L, and 12.7 mg/L, respectively (Figure 5-5). The observed TSS removal efficiency for discharge of 80% was 58% which was greater than the removal efficiency for discharges of 20%, 40%, and 60%. The TSS reduction pattern for discharge of 80% showed a similar pattern as of discharges of 40% and 60%.

The observations for the TSS levels at sample points A, B, C, and D for the discharge of 100% were 40.4 mg/L, 30.2 mg/L, 22.7 mg/L, and 19.7 mg/L, respectively (Figure 5-5). The TSS reduction pattern for discharge of 100% showed a similar pattern as discharges of 40%, 60%, and 80%. The observed TSS removal efficiency for discharge of 100% was 47% which was greater than the expected removal efficiency as per the design proposal.

The average TSS levels for discharge of 100% at each sampling point was depicted in Figure 5-6. As per the bar chart depicted in Figure 5-6, the BOD removal rate was reduced from sample point A to sample point D. In addition, the predicted level of TSS to the constructed wetland was around 39.0 mg/L with a standard deviation of 5.7mg/L (Figure 5-6). An average TSS levels at sample points B and C were 30.3 mg/L (standard deviation = 4.8 mg/L) and 23.0 mg/L (standard deviation = 4.6 mg/L), respectively. The average TSS level at the outlet point (sample point D) was 20.3 mg/L (standard deviation = 5.2 mg/L) (Figure 5-6).

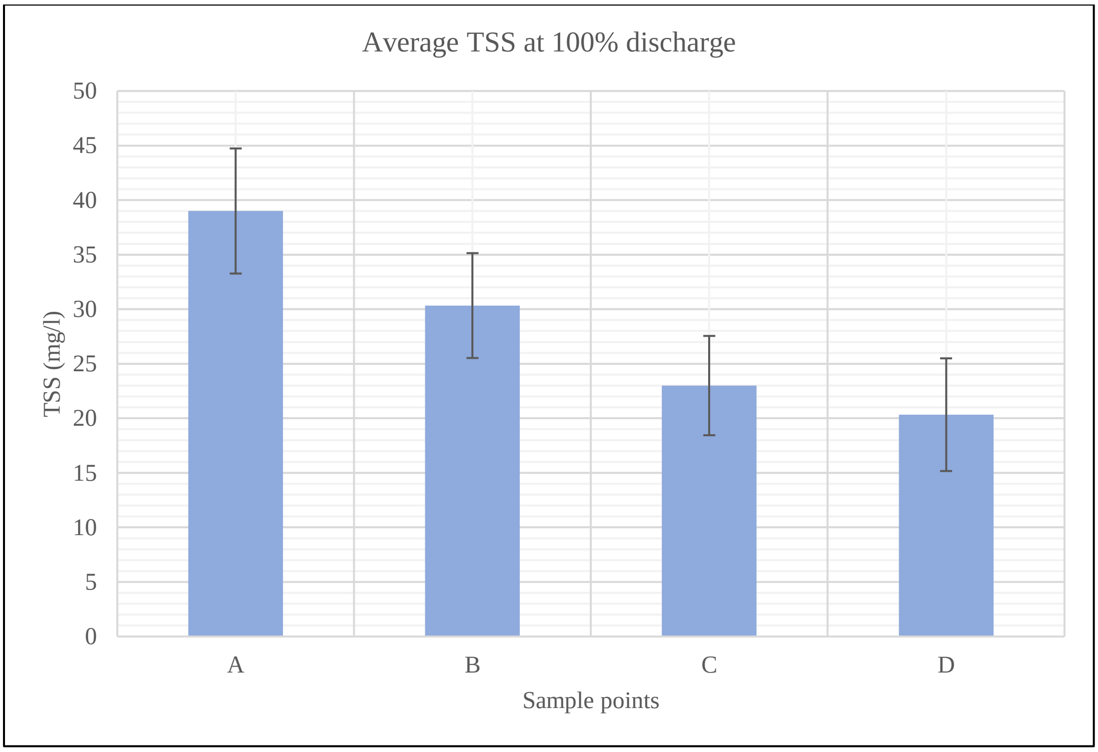

Figure 5-7: Average values of TSS at each sampling point

5.3.4. Changes in TKN

The highest TKN value was observed in point A at all discharges. The TKN values at point A eventually corresponded with the influent water quality because it increases with the increment of percentage discharge (Figures 5-7 and 5-8).

Initially, at 20% of the discharge, points C and D showed elevated values of TKN than points A and B. At a 40% flow rate TKN value in point C increased and reduced at point D. However, it is observed that point C had a higher value than point B whether the percentage discharge is increased. At the discharge of 40%, it is observed an elevated value for TKN at point C compared to the discharge of 20% at point C. It could be associated with a sampling error.

When considering the discharge percentages, at 20% we observed the highest TKN value at point D, which is greater than the influent water quality value (at Point A). However, TKN values at point D were reduced (Figures 5-7 and 5-8). We observed a reduction pattern at 60% of discharge whereas discharges of 40% and 20% did not show a reduction pattern (Figures 5-7 and 5-8).

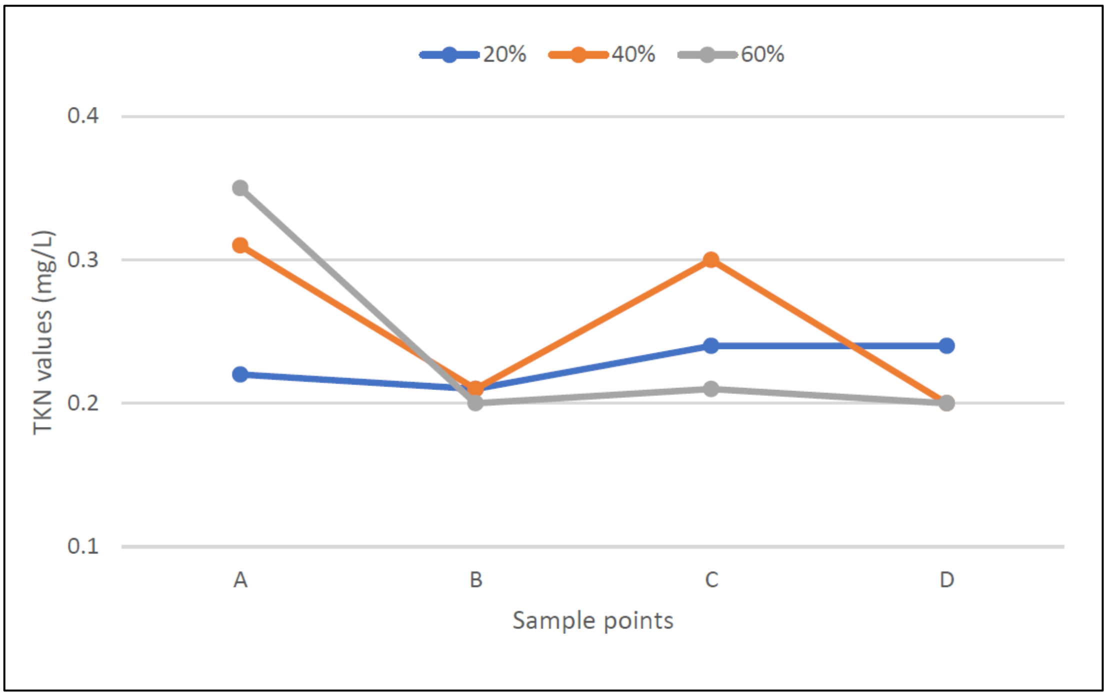

Figure 5-8: Changes in TKN levels for different discharges

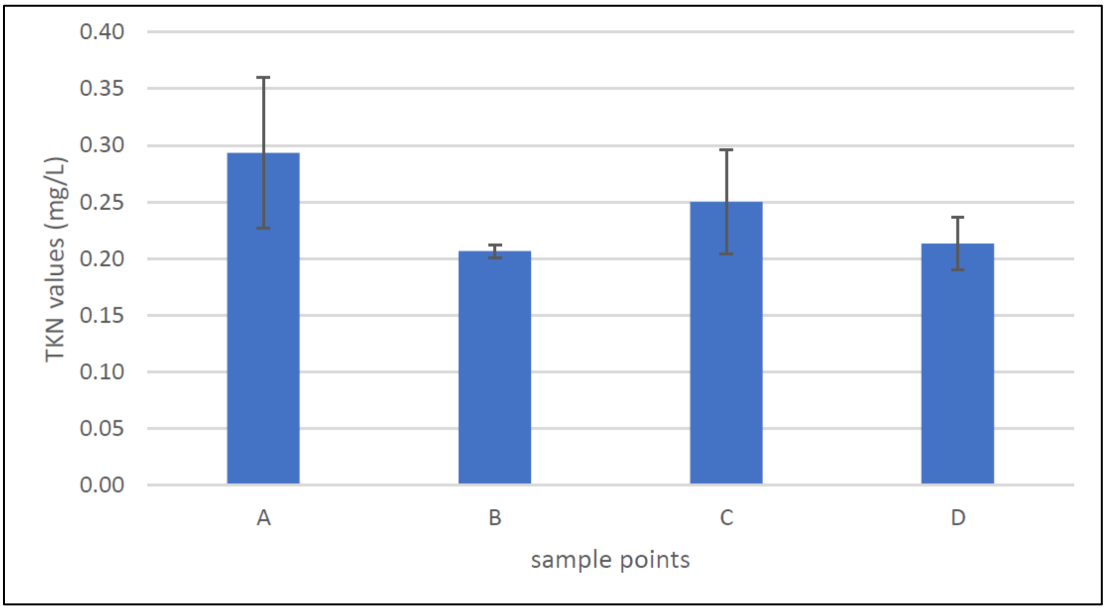

Figure 5-9: Average values of TKN at each sampling point

Considering the average TKN values at each sampling point, we observed that the point D values increased more than the point C values. However, a reduction was observed between points A and B. The results demonstrate TKN reduction across points A and D during the data collection period. The removal efficiencies between points A and B are higher than points C and D. Moreover, considering the percentage discharge, a discharge of 60% has a removal efficiency rate of 42.9%, which is higher than removal efficiencies if discharges for 40% and 20% (Figures 5-7 and 5-8 and Table 5-1). As per the observations, the TKN removal efficiency of 25% met the guidelines stipulated by CEA.

5.3.5. Changes in TP

The highest TP value has been observed in point A at all discharges. When increasing the discharge percentage, the point A values were increased eventually and corresponded with the effluent value (Figures 5-9 and 5-10).

At the discharge of 20%, point C did not show a reduction in TP levels. However, at a discharge of 60%, point D showed the same TP level as discharges of 20% and 40%. When considering the percentage of discharges, a reduction pattern was observed at discharges of 60% and 40%, while at the discharge of 20%, it did not show a reduction pattern. Moreover, TP followed a similar pattern at discharges of 40% and 60%, but a different pattern at the discharge of 20% (Figure 5-9 and 5-10 and Table 5-1).

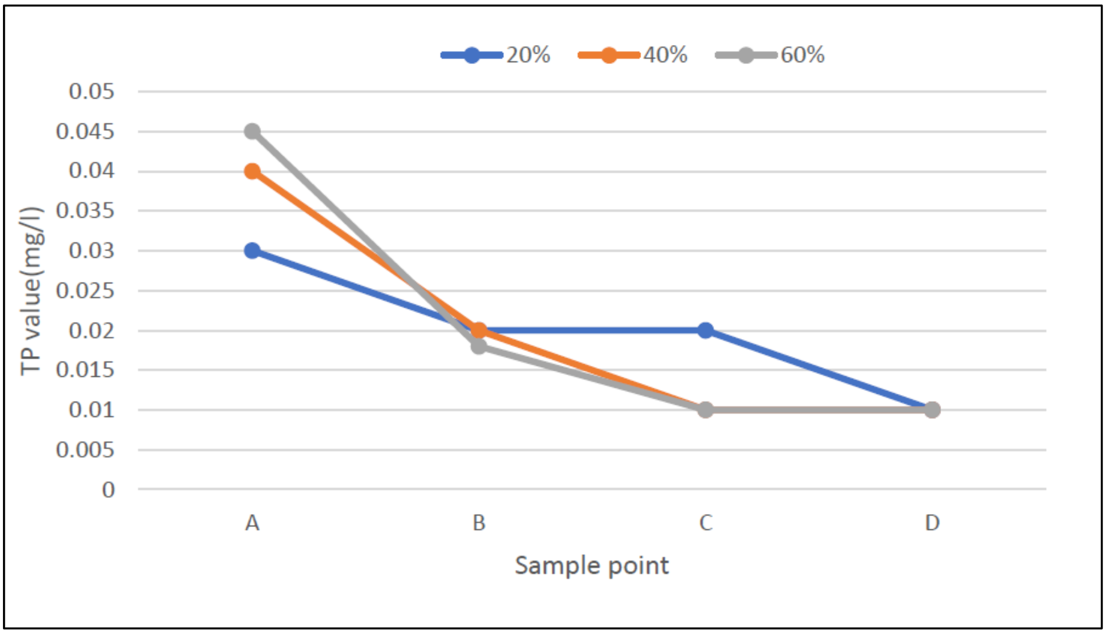

Figure 5-10: Changes in TP levels for different discharges

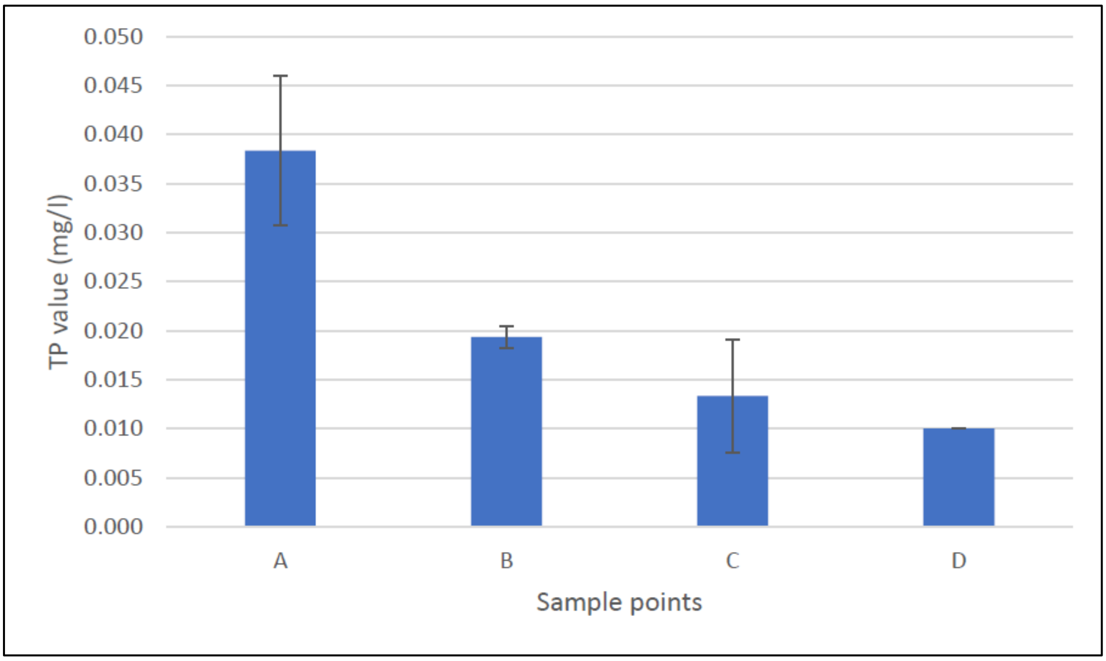

Figure 5-11: Average values of TP at each sampling point

Considering the average TP values at each sample point, a reduction was observed at each sample point. However, there is a higher reduction between points A and B than other points.

The results demonstrate TP reduction across points A and D during the data collection period when the system was exposed to similar nature wastewater. A higher removal efficiency between points A and B can be observed when compared to other points. Furthermore, considering the percentage of discharges, a discharge of 60% obtained the highest removal efficiency of 77.8% which is greater than the removal efficiencies obtained for 40% and 20% (Figure 5-9 and 5-10 and Table 5-1).

The removal efficiency of the TP is 73% which met the design criteria and the water quality for TKN stipulated by CEA.

5.3.6. Changes in Temperature

The temperature distribution was in the range of 27 °C – 32 °C for all the discharges. The temperature variation for the discharges of 20% and 40% is negligible. The almost same temperatures were obtained at sample points A and B for this discharge.

However, discharges of 60%, 80%, and 100% showed a decline in temperature from sample points A to D (Figure 5-11). The declining pattern was observed because the water tends to reach equilibrium status when it changes its environment to a constructed wetland. An increasing pattern was observed in temperature levels at sample point A with the increase in discharge percentages (Figure 5-11). The reduction of temperature for discharge of 100% is significant compared to the reduction of temperature for other discharge percentages (Figure 5-11). The temperature at the sample point D of discharge of 100% was a little lesser compared to the temperature of discharges of 60% and 80%.

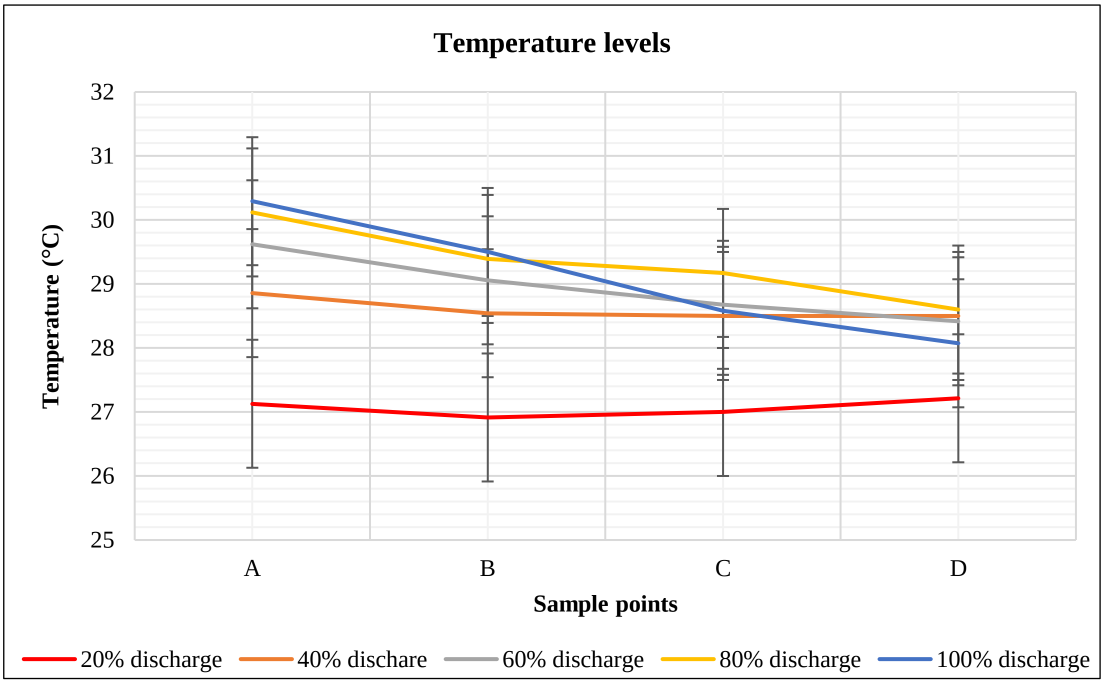

Figure 5-12: Changes in temperature levels for different discharges

The temperature distribution for the discharge of 100% was depicted in Figure 5-12. The temperature at sample points A, B, C, and D are 30.3 °C, 29.5 °C, 28.6 °C, and 28.1 °C with standard deviations of 1.0 °C, 0.8 °C, 0.6 °C, and 0.5 °C, respectively. The difference in temperature at sample points A and D is 2 °C. The temperature at the inlet to the constructed wetland is almost similar to the ambient temperature; hence, the variation of temperature is very little. According to the reported temperature levels, the removal efficiencies of contaminants at each sampling point may not influence the effects due to the temperature.

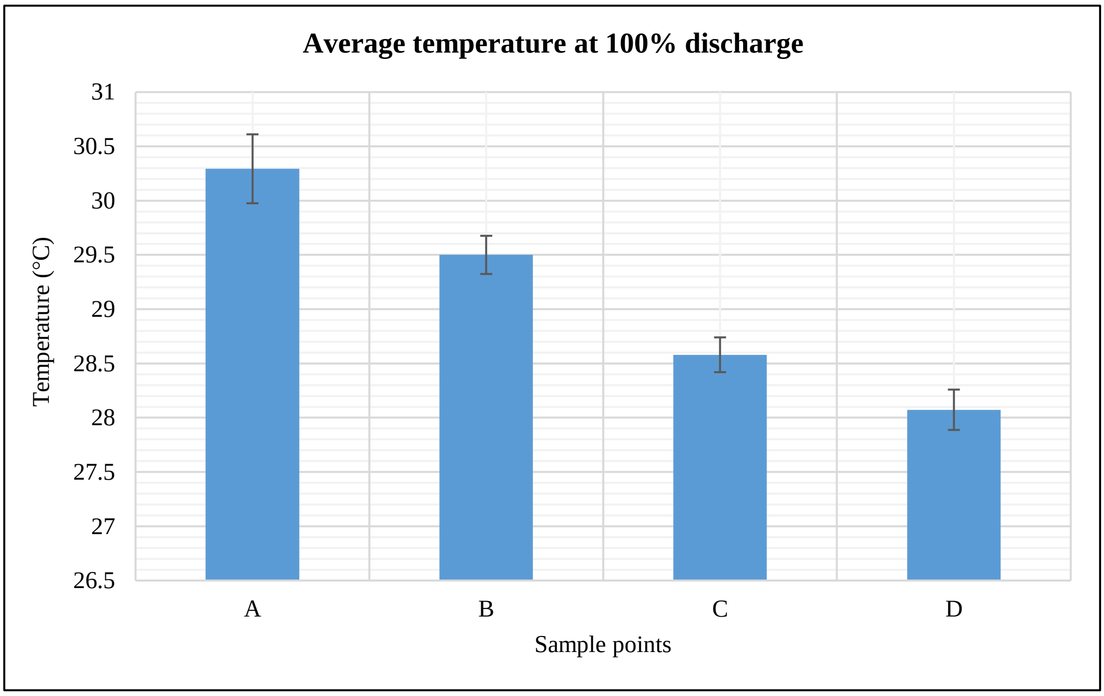

Figure 5-13: Average values of temperature at each sampling point

5.3.7. Changes in pH

The observed pH values are in the range of 7-7.6. A slight increase in pH range was observed from sample points A to B for discharge of 20%. Then, a decline from sample points C to D. Similar pattern was observed for discharge of 40% at sample points A, B, and C (Figure 5-13). However, an increment was observed at sample point D. However, all the observed pH values agreed with the typical pH of surface water.

The reduction pattern in pH was observed for discharges of 40%, 60%, and 80%. The average pH at sample point A was almost the same and the pH reduction rate was less when the discharge of 60% compared to discharges of 80% and 100% (Figure 5-13). The pH at sample point D for the discharge of 100% was 7.0 (Figure 5-14).

The observed pH values showed that the water discharged into the constructed wetland did not show any acidic nature; the water is almost at the neutral condition. For all the discharges, pH fluctuations were observed in a very small range. The observed pH values were acceptable according to the standards stipulated by CEA; 6.5 to 8.5 for inland surface watercourses.

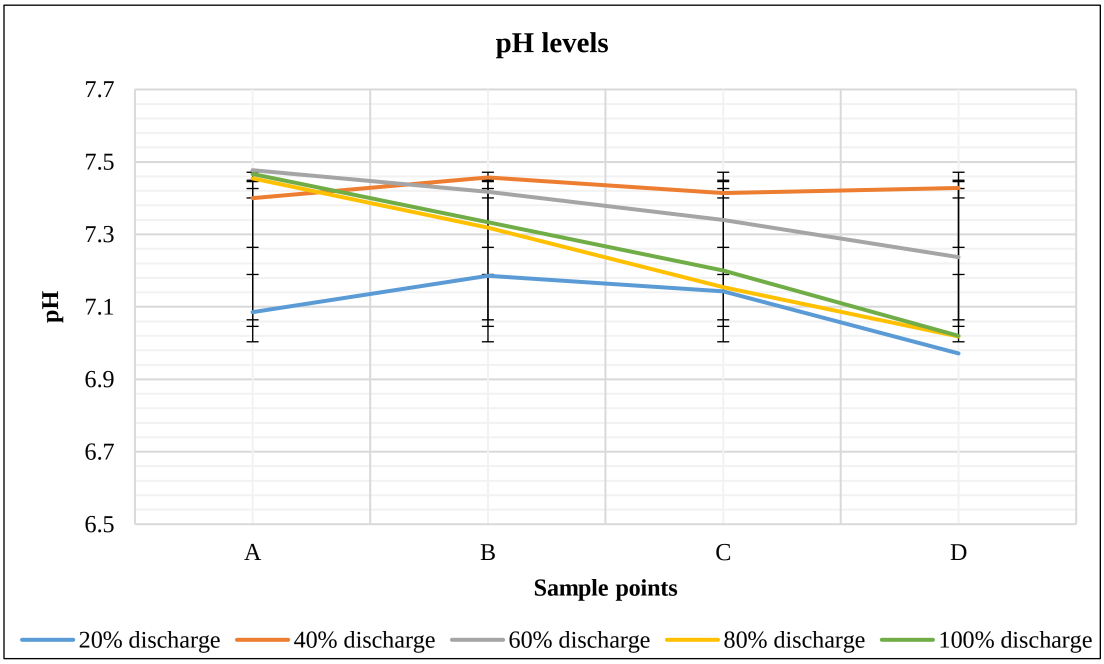

Figure 5-14: Changes in pH levels for different discharges

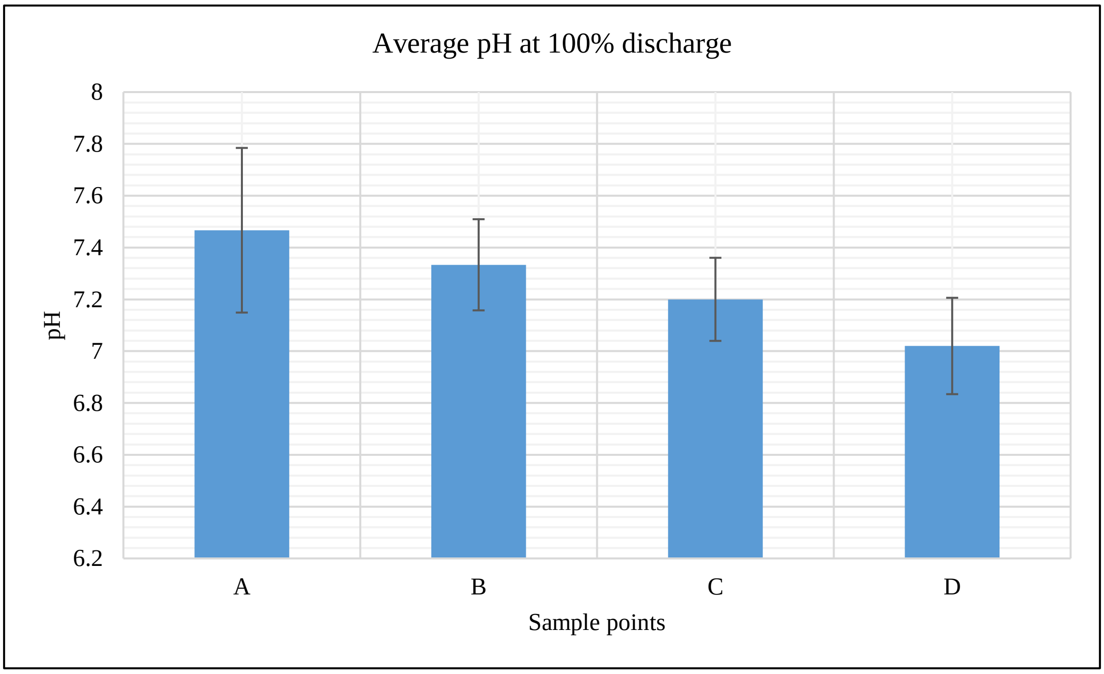

Figure 5-15: Average values of pH at each sampling point

5.3.8. Changes in Faecal Coliform

The observation for faecal coliform levels is collected for selected sample points only; hence the data was not available for all the sample points. However, the collected data showed faecal coliform levels were less than 2 MPN/100 ml throughout the data collection period. There was no elevated difference in faecal coliform levels in points A and D.

All faecal coliform values in treated water from CW are within acceptable levels compared to the guidelines stipulated by the CEA for inland surface watercourses.

6. DISCUSSION

The main objective of the research study was to recommend CW to the textile industry as a tertiary treatment method. Assessing the performance of the constructed wetland as a tertiary treatment in terms of contaminant removal efficiency was the secondary objective. The results obtained during the research study are discussed in this chapter.

6.1. Performance evaluation of the constructed wetland

The constructed wetland used in this study yielded high removal efficiency of COD, BOD, and TSS than the specified values in the design proposal. Temperature and pH values were maintained at an acceptable level for the discharge. Faecal bacteria were not detected in the system.

6.1.1. Design parameters of the CW

The CW was constructed in a marshy area with 2 acres of land extent. The selected area is fully covered with the invasive species (Annona glabra) to avoid/minimize the effect on the ecosystem due to the effect of the proposed concept. The land was dilapidated having peat soil conditions. Also, it was near the proposed treated effluent discharged canal. Therefore, the selected area is suitable for the constructed wetland.

Phragmites karka has been identified as a naturally occurring plant in the area. The plant is effective in the removal of contaminants; the absorption rate of Nitrogen and Phosphorous is high. Therefore, *Phragmites karka* is selected as the vegetative cover of the CW (Figure 6-1). The ecosystem was not disturbed because of the *Phragmites karka* because it is naturally available in the area. The absorbed contaminants accumulate in the plant species. It is released directly through excretion from the leaves of the plant. In addition, it releases when the plant becomes detritus. The rapid growth pattern allows replacing of dead plants with new plants without hindering the performance of the CW (B.-H. Lee & Scholz, 2007)

Burnt clay from the tile industry was selected as the substrate medium as depicted in Figure 6-2. The substrate was selected in terms of local availability, cost, hydraulic aspects, technical feasibility, support for plant growth, microbial adhesion, the life span of the material, disposal issues, and potential for contaminant removal (H. Wang et al., 2018).

Figure 6-1: Vegetative cover of the CW

Burnt clay has higher porosity due to its heating to around 1,200 °C (2,190 °F) in a kiln, resulting in a honeycomb structure. This increased the absorption capacity, which is effective in Phosphorous and Ammonium removal (Baiden et al., 2014). Also, the higher porosity with a big particle size reduces the clogging in the substrate (Ramprasad et al., 2017). It leads to the high sustainability of the CWs. Burnt clay is a cost-effective substrate material that is locally available. Further, burnt clay does not harm the ecology. It has long durability and its ability to be safely disposed of without any secondary pollution to the environment is an extra benefit. Burnt clay as a substrate for the CW is a sustainable approach to the local context.

Figure 6-2: Broken burnt clay

The water flow pattern through the CW significantly influences the efficiency of the CW. The removal efficiency of BOD, COD, and TSS increased with hydraulic retention time (HRT) (Kuschk et al., 2003). HRT of CW can increase due to the vegetation cover and the substrate. However, HRT can increase by implementing inter-barriers to separate the wetland (Mayo & Mutamba, 2004). The inter barriers were placed such that the zig-zag configuration is maintained for the water flow. This configuration is imperative to utilize the whole wetland area efficiently and effectively. No dead zones are expected within the whole wetland area.

The CW should prevent seepage of the pollutants into the groundwater table. Horizontal flows may occur as leakage from or into the wetland, depending on the transmissivity of the substrates (C. S. Akratos & Tsihrintzis, 2007). Therefore, impermeable liners will be utilized whenever necessary. Geotextile fabric was placed on contacting area of the wetland; bottom and the bunds of the CW) to avoid the penetration of the toxic material into the water table. Geotextile is more cost-effective than impermeable liners and efficiently eliminates contamination.

6.1.2. Removal efficiency with respect to the selected vegetation and substrate

The emergent plants help with wastewater treatment in various ways, including settling suspended materials, increasing surface area for microbes, and releasing oxygen(Brix et al., 2011; Cheremisinoff, 2001). This study used Phragmites spp. (*Phragmites karka*). Moreover, due to its rooting system and the growth rate, offering the essential habitat for the growth of decomposing microorganisms resulting increase in biodegrading and helping to tolerate the shock loads and extreme conditions. Some samples were taken during wet weather, which allowed dilution of the wastewater influent and high values from surface runoff into the wetland from the catchment. The results confirmed that the presence of plants would boost the reduction of COD and BOD in specified units for adopted concentrations. We observed optimum removal efficiency at the high-density area of *Phragmites* spp, which helps to biodegradation process by facilitating the decomposing microorganisms.

The reduction of TKN may occur due to the intake by the plants and oxygen release from the plant root providing a favourable influence on nitrifying bacteria in the rhizosphere. In this study also, we observed optimum removal efficiency at the high-density area of *Phragmites* spp. Several experiments on TKN removal in treatment wetlands revealed that the unplanted treatment removed less TKN than the planted treatment (Hijosa-Valsero et al., 2010). However, we observed an increment of TKN in point C at all flowrates, and the 40% flowrate observed an elevated value. Although constructed wetlands have been shown to be capable of removing Nitrogen, nitrogen removal effectiveness has been (B.-H. Lee & Scholz, 2007) uneven due to a lack of understanding of nitrogen transformation and removal mechanisms (Spieles & Mitsch, 1999). This could be happened due to a sampling error as well.

The wetland profile of each parameter showed a correlation with the vegetation cover of the wetland. We could identify value increments in points C and D for some discharge percentages, but we could not in points A and B. It showed the importance of vegetation in the wetland for the removal process. At points B and C, we observed less density of vegetation cover. This may happen due to the less nutrient content in water for the plants. In the initial area, the plant got enough nutrients from the wastewater (Nitrogen, Phosphorus) for plant growth. However, when going further, the plant may not get enough nutrients for its growth resulting in less vegetation cover. Point D considers the fishpond, which has less wetland vegetation. Moreover, we could identify the correlation when considering the removal efficiency at each sample point.

6.1.3. Removal efficiency with respect to the substrate

Substrates in CWs are strongly connected to the other core aspects and substantially impact their performance and long-term sustainability. Subsequently, CWs have been used to treat complex pollutants from various fields, resulting in a new demand for substrates to improve CW performance and durability (B.-H. Lee & Scholz, 2007). Our study used Calicut tiles as the substrate media, which may act as a high-absorption media. For COD removal, Calicut tiles media play an essential role by accumulating significant amounts of adherent microorganisms, helpful in rapidly accelerating biochemical reactions. In point D, the COD values increased at some discharges, but the substrate area of the constructed wetland showed a reduction. Phosphorus removal is not usually a design priority for most HSSF-CWs, instead designed to remove COD, BOD, and TSS.

Several studies have examined the use of constructed wetlands to remove Phosphorus from wastewater (Mann & Bavor, 1993; Richardson, 1985; Sakadevan & Bavor, 1998). In wetlands, total phosphorus removal is a multi-step process. To eliminate various Total phosphorus components, physical, chemical, and biological functions are used. Plant absorption, microbial immobilization, accretions of wetland soils, precipitation in the water column, and substrate retention could all assist in total phosphorus removal in constructed wetlands (Richardson, 1985). Soluble Phosphorus will move with the water flow in subsurface-flow wetlands, but Phosphorus linked with particle matter will be regulated by filtration and absorption systems in the wetland bed (Kadlec & Wallace, 2008). (Kadlec and Wallace 2009).

In our study, most Phosphorus is thought to be deposited in the substrate rather than plant uptake. Due to adsorption capacity saturation, the total phosphorous removal effectiveness rapidly decreased as the wastewater passed through the CW. This may be an arising conflict to confront with the constructed wetland.

6.1.4. Effectiveness of contaminant removal and its efficiency

The influent on the CW varied from 20% to 100% during the study period to let the plants familiar with the contaminated wastewater. During the period the pH and the temperature of the CW maintains almost similar. The climate of Sri Lanka does not show significant temperature differences during the year. Therefore, the effect due to the temperature kept similar throughout the year.

The BOD removal efficiency was 35.1% higher than the expected BOD removal level. The *Phragmites* species service in the biodegradation process with the assistance of decomposing microorganisms are the major reason for the effective and efficient BOD removal (García-Ávila et al., 2019). The basic treatment mechanisms of the BOD removal from the CW is the microbial interactions (Reed et al., 1998)

A similar process is applied for the COD removal efficiency; hence, 27.3% higher COD removal efficiency was observed compared to the expected removal rates in the initial proposal.

It is observed that well-planted species-area obtain a high nitrogen removal rate than other areas. The vegetation cover used in the constructed wetland in *Phragmites* species. It evoked that the *Phragmites* species are effective and efficient in nitrogen removal (García-Ávila et al., 2019). In the CW, the denitrification process is capable of 60-70% nitrogen removal whereas 20-30% of that is as a result of plant uptake (Spieles & Mitsch, 1999). Further, a high tolerance level for extreme conditions was observed in the areas where the vegetation cover is rich (Figure 5-8). The observed nitrogen removal rate is low indicating poor denitrification in the CW. However, Billore and his co-workers showed that the NH_4-N removal efficiency was around 78% (Billore et al., 1999). They further elaborated in their research that the NO_3^--N removal efficiency was low; around 2.38%. However, the design proposal did not provide the expected efficiency for the TKN contaminant. Hence, the observed efficiency of 25% for TKN is accepted and possible measures are to be implemented after successful reviews. The possible mechanisms for nitrogen removal from CW include adsorption, volatilization, plant absorption, ion exchange, plant uptake, and nitrification & de-nitrification. The dominant mechanisms for nitrogen removal from the CW are not clear (Billore et al., 1999).

The observed TP removal efficiency of 73% was achieved and accepted as no required efficiency levels are stipulated in the design proposal. The probable mechanisms for Phosphorous removal from CW may include plant uptake, complexation reactions, biological interactions, and adsorption (Billore et al., 1999; Mann & Bavor, 1993; Richardson, 1985). The predominant P removal mechanism was identified as the retention of P in the substrate (Sakadevan & Bavor, 1998).

The TSS removal efficiency of 47.2% was observed. The removal mechanism of the TSS is a physical separation process (T. H. Davies & Cottingham, 1994; Shutes et al., 1997; Zachritz & Fuller, 1993). The substrate properties determine the retention of solids. The burnt clay tile particles create filtering media such that the expected efficiency can be obtained. Further, the selected substrate media is less compatible; hence higher efficiencies can be obtained (Manios et al., 2003).

Considering the observed efficiency for the contaminant removal from the CW, it seems that the probable mechanisms for contaminant removal vary based on the design of the CW. However, the influence of the vegetative cover and the substrate are significant factors for the performance of the CW. Based on the observed results the CW can be proposed as an effective mechanism to implement as tertiary wastewater treatment for textile wastewater.

Based on the parameters assessed at three discharges over a short period, it indicated that the removal efficiency of Nitrogen and Phosphorus is high, and the constructed wetland is well performed. The parameters assessed at full discharge over the period indicated that the removal efficiency of BOD, COD, and TSS is also within the expected limits. Therefore, the research study proved that the design and theoretical considerations were accurate.

The efficiency of the contaminant removal was varied with respect to the discharge percentages. The discharge percentage influenced the organic compounds in the CW (Saeed & Sun, 2012). Therefore, the degradation of more organic matter by microorganisms clusters in the substrate and the roots took place with a higher discharge percentage. However, the plant requires time to familiarize itself with that contaminant loading; hence there should be a time gap to increase the discharge percentage.

The sub-surface flow CWs system is succus in eliminating suspended solids through sedimentation and filtration (Kadlec & Wallace, 2008). Therefore, the observed removal pattern of TSS in all discharges allowed the settling of more suspended solids. However, in the 20% discharge, the elevated value of TSS in point D can be due to the addition of more silts particles from the fishpond to the low-velocity flow.

Slow water flow helps to transfer the temperature and cool the water. However, when the surface area increases, there is the possibility of increasing water temperature. However, we observed that temperature did not change drastically throughout the constructed wetland in this study. However, at point D, observed an elevated increment due to the fish respiration and the biodegraded organic matter within the fishpond.

6.1.5. Proposed maintenance plan of CW

The technical person appointed to the WWTP will look into the overall operation and maintenance works of the CW. Besides, a technician and two laborers will be assigned to routine work. The tasks assigned to each person are depicted in Table 6-1.

Table 6-1: Appointed responsible personnel and their tasks

	Designation	Tasks assigned
1	In charge of the WWTP (01 No.)	- Look into the overall operation and maintenance works of the CW

		- Check the quality of treated effluent quality - Check the working schedule of the technician and laborers assigned for the routine works of the CW
2	Technician (01 No.)	- Inspect the operating condition of E&M equipment installed - Check the schedule of maintenance of the pumps together with the checklist filled at the end of each periodic maintenance - Check the availability of contact details of the pump supplier/local agent - Check the working schedule of the laborers assigned for the routine works of the CW
3	Laborers (02 Nos.)	- Carryout the routine operations and maintenance works - Attend rectification works of E&M equipment when required

6.1.6. Limitations of the research

Technical limitation of the research study is as follows:

- We initially planned to increase the flowrate with a 2-week time gap. However, we observed that the time gap might not be enough and have to give more time for plants to adapt to the pollutant level high flowrates.
- Thus, the increment time gap should be more than two weeks in practice. It restricts the time availability of the study.
- This study has to stop in the middle due to the time restriction but has to further cover the dry and rainy seasons to obtain more accurate results.
- We started the data collection during the dry season to avoid other influence factors. However, being unexpectedly exposed to stormy weather conditions

led to changes in some parameters. Hence, 40% of the flowrate results in changes unexpectedly.

- We could not provide a continuous flow to the constructed wetland due to the factory being closed on government holidays.
- For TKN and TP measured, samples were transferred to the Environment Laboratory at the University of Moratuwa. For QA purposes, filed blanks and trip blanks were not taken.

Study design limitations are as follows:

- This study only monitored a few essential parameters. However, to obtain an accurate result, it should test for more parameters, dissolved nutrients, and microplastics.
- The study should undertake for a more extended period covering both dry and wet weather periods.
- The *Phragmites* coverage across the CW, the condition of the soil in the CW, and the groundwater table of the area change and its effect on absorbing pollutants.
- The study did not check the ongoing health of the fish. Only looked at fish mortality in response to effluent. Fish may be suffering from chronic health effects due to sublethal toxicants, which could only identify after some time and fish tissue pathological test.

7. CONCLUSION

Textile wastewater treatment evolved into a national concern that effects flora and fauna in the environment. Among the wastewater from industries, effluent from the textile industry is the leading contributory factor to water pollution. Sri Lanka is the leading exporter of apparel and textile products in the world, is of utmost importance to evaluate the quality of the effluents discharged from the related industries to the environment. During the process of textile manufacturing, various types of dyes and chemicals are used. Textile effluents consist of several synthetic dyes and toxic chemicals. Generally, biological, physical-chemical, and combined treatment processes are applied to the textile wastewater before its discharge into the surface waterbody or municipal sewage

In recent decades, the need for tertiary treatment to remove the excessive levels of pollutants, contaminants, and salts from textile effluents is gaining attention to reduce surface water contamination. Further, the capability to meet the permissible levels of contaminants or pollutants according to the statutory requirements should be focused on to determine the effectiveness and efficiency of tertiary treatments in terms of final effluent quality. The future trends in implementing suitable tertiary wastewater treatment in the textile industry focus on sustainable solutions mostly. The past two decades showed dramatic changes in water treatment approaches where the need for tertiary treatments for textile wastewater is comprehensively analyzed in terms of lower capital and operational maintenance cost, efficiency rates, operational procedures, final effluent quality, and waste production at the end of the process. Previous research studies have shown that the performance of constructed wetlands as tertiary treatment to textile wastewater is a successful initiative.

A modern WWTP with a capacity of 1,000 m^3/day to treat the process wastewater and domestic wastewater generated from the factory to minimize environmental harm. The quality of treated effluent complies with the tolerance limits for industrial wastewater discharge into inland surface waters. To enhance the treated wastewater quality as per the CEA request and ensure that no toxic compounds are in the treated wastewater discharged into the nearby canal, the company proposed a constructed wetland and fishpond amalgamated into the existing wastewater treatment plant. A marshy area neighboring the canal has been selected to construct and implement the constructed wetland. The land extent is 2 acres and is dilapidated land. The area was previously used for paddy cultivation. The land is covered with ‘Wel Atha’ plants. A peat soil condition is observed. The proposed land is situated in the flood plain of the canal; hence it goes under water easily during the wet season.

The conceptual design of the constructed wetland is to remove BOD, COD, TSS, Nitrogen, and phosphorous in the effluent by giving a polishing step before discharging into the canal. The fishpond is paired with the constructed wetland to act as a Bio-indicator for the quality of effluent.

The proposed wetland is a type of subsurface flow with no water column. Broken brunt clay was utilized as the plant growth medium because it has a 50% void ratio, allowing treated wastewater to flow easily through the wetland. A metal chip layer was placed on the geotextile to prevent the treated water from penetrating the water table before the broken brunt clay was laid. Roofing sheets are used to maintain the zig-zag shape to avoid short-circuiting. When designing a fishpond, special attention was paid to ensuring that the specified requirements were met. DO levels are sufficiently maintained by ensuring proper fish density and, if necessary, the addition of artificial bubble plumes. It was planned to introduce common carp or European carp, Common fish species

The research study expected removal efficiencies of 45.0%, 16.7%, and 15.0% for COD, BOD, and TSS, respectively. However, observed efficiencies are greater than the expected removal efficiencies, hence, satisfactory. The average COD levels observed for discharge of 100% at sample points A, B, C, and D were 160.5 mg/L, 64.0 mg/L, 52.6 mg/L, and 44.3 mg/L, respectively which are acceptable as per the guidelines stipulated by the CEA; 250 mg/L for inland surface watercourses. At a discharge of 100%, the BOD level at sample point D was acceptable as per the guidelines stipulated by the CEA; 60 mg/L for inland surface watercourses. The observations for the TSS levels at sample points A, B, C, and D for the discharge of

100% were 40.4 mg/L, 30.2 mg/L, 22.7 mg/L, and 19.7 mg/L, respectively (Figure 5-5). The TSS reduction pattern for discharge of 100% showed a similar pattern as discharges of 40%, 60%, and 80%. The observed TSS removal efficiency for discharge of 100% was 47% which was greater than the expected removal efficiency as per the design proposal. As per the observations, the TKN removal efficiency of 25% met the guidelines stipulated by CEA. The removal efficiency of the TP is 73% which met the design criteria and the water quality for TKN stipulated by CEA. The temperature at the inlet to the constructed wetland is almost similar to the ambient temperature; hence, the variation of temperature is very little. According to the reported temperature levels, the temperature at each sampling point may not have an influence on the effects due to the temperature. The observed pH values showed that the water discharged into the constructed wetland did not show any acidic nature; the water is almost at the neutral condition. For all the discharges, pH fluctuations were observed in a very small range. The observed pH values were acceptable according to the standards stipulated by CEA; 6.5 to 8.5 for inland surface watercourses. The observation for faecal coliform levels is collected for selected sample points only; hence the data was not available for all the sample points. However, the collected data showed faecal coliform levels were less than 2 MPN/100 ml throughout the data collection period. There was no elevated difference in faecal coliform levels in points A and D.

The study suggests that, if appropriately operated, constructed wetlands might have been effectively utilized for secondary and tertiary wastewater treatment under local circumstances. As a result, constructed wetlands can be included in the treatment process to modify existing underperforming wastewater treatment plants. These wetlands' treated wastewater could be used for irrigation and other practical purposes. Further research is needed to study a pattern of vegetation nutrient uptake throughout dry and wet seasons and the nutrient absorption capacity of the substrates. In this study, we used Phragmites species for the vegetation cover. However, we could further use *Typa* species to identify more Nitrogen and Phosphorous removal. This study used Calicut tiles as the media to obtain more absorption of heavy metals, Nitrogen. However, with time, they may be reached the maximum absorption rate. Therefore, further research to be done to identify the durability of the Calicut tiles. Chemicals used for the process may have to change due to several reasons. The main one is the cost. Therefore, have to test for those chemical recipes by using a constructed wetland cell using identical conditions for the performance. It is more convenient to use biodegradable chemicals that may not affect the wetland vegetation. Also, we need to assess the efficiency of the CW over time due to removal efficiency of the wetland will be reduced with time, and it will negatively affect the environment.

Finally, the CW can be successfully implemented as a tertiary wastewater treatment method in the textile industry under local conditions.

8. RECOMMENDATIONS

The following recommendations were made to ensure the sustainable functioning of the CW as a tertiary wastewater treatment method.

1. Continuous research studies shall be done to improve the CW performance based on the changing characteristics of the textile wastewater
2. Study the effectiveness of CW as a green concept to other industries where the wastewater characteristics are varied.
3. Study the effect of groundwater table in terms of water pollution due to possible contaminations.
4. Arrange workshops to train the stakeholders to promote green concepts in the field of wastewater treatment.
5. Apply market-based instruments wherever necessary, such that effective functioning of the CW can be obtained.
6. Private sector participation should be encouraged to construct and implement the CW as a green concept.
7. The contaminant removal mechanisms with respect to the different wetland plants and substates should be studied to get the optimum use from the CW to remove the contaminants.
8. Environmental Policy network shall be used with the sufficient legal backing to improve the effectiveness of the implementation of the proposed CW functions under the study
9. The availability of annual performance monitoring, recording, and reporting systems shall be made legally mandatory for service providers.
10. The establishment of laboratories with trained staff will be accompanied to monitor the quality of the final effluent.

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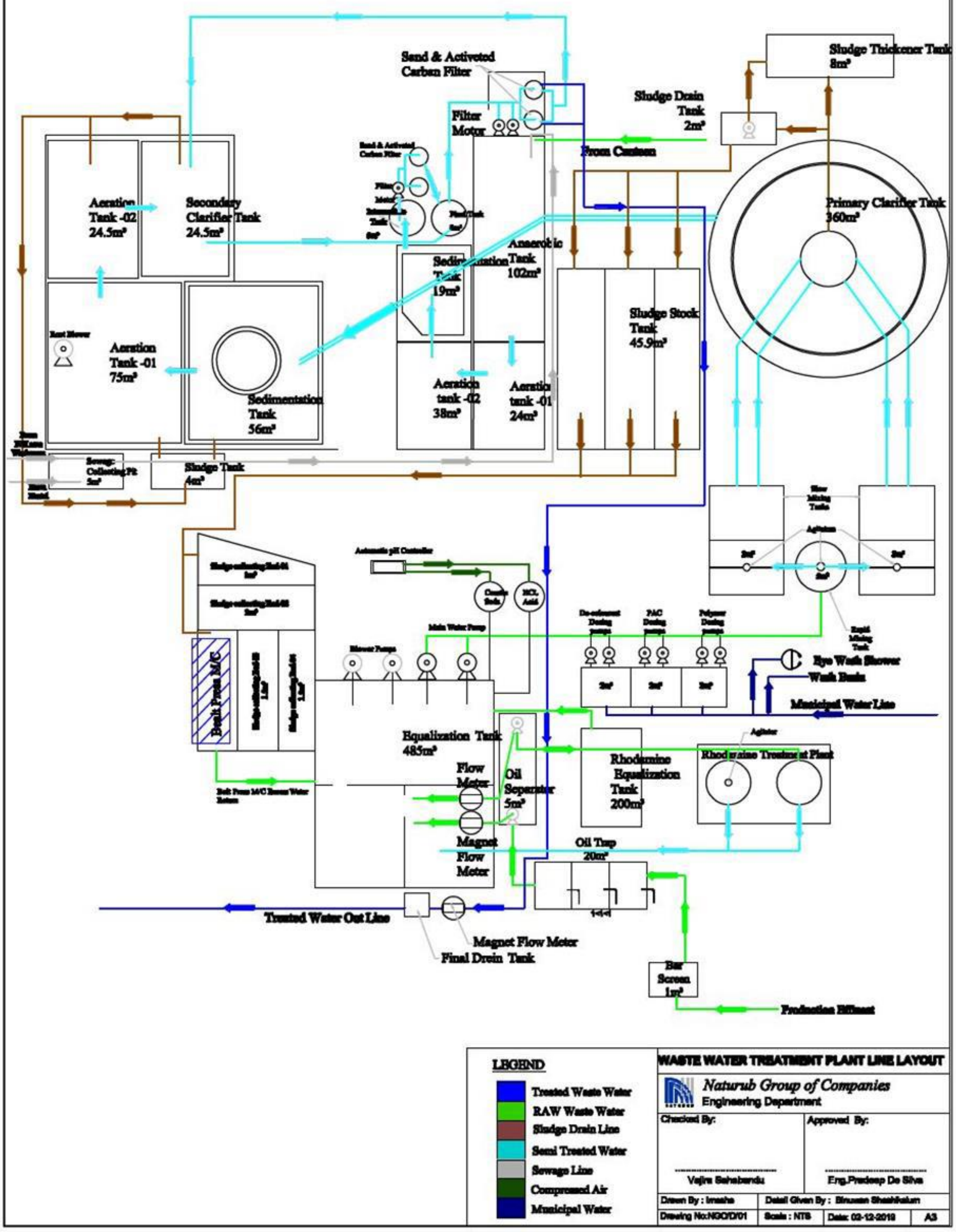
APPENDIXES

Appendix 1-1: Figure 2: Process flow diagram of the WWTP

(Source: Naturub Exports International (Pvt) Ltd, 2021)

WASTE WATER TREATMENT PLANT LINE LAYOUT



Appendix 4-2: Determination of pH and Temperature

Determination of pH and temperature

A portable multimeter (HI-9813-6, HANNA) was used to measure the pH and temperature. Before measuring the sample, calibrated the meter and electrode system using a pH buffer solution (Appendix 4-8). The sample (250 ml) was taken into a clean glass beaker. Gently clean the electrodes with suitable blotting paper after rinsing them with distilled water. The electrodes should then be immersed in the sample and stirred at a constant rate to produce homogeneity and stabilize the readings.

Appendix 4-3: Determination of BOD

Determination of BOD

A five-day BOD test (5210B) was performed according to APHA guidelines (2017). The dark bottle (250 ml) was filled with water without trapped air. The sample vial was filled with manganese sulfate solution (1 ml) and rapidly shaken to measure the initial dissolved oxygen concentrations (Appendix 4-8). The sample bottle (250 ml) was bought into the laboratory and incubated in the dark for five days at 20 °C to determine the dissolved oxygen after the five-day (DO_5) interval.

Similar to the water samples, two dark bottles (250 ml) were filled with dilution water to measure the initial DO and DO after five days. The precipitate in the bottle used for the determination of initial DO (DO_1) was dissolved with concentrated sulfuric acid (1 ml) at the processing time. A portion of the sample (100 ml) was pipetted out and subsequently titrated using sodium thiosulphate titrant (0.025 M) and starch as an indicator.

The diluted sample, collected to determine the DO after five days (DO_2), was subjected to the same process. The following formula was used to determine BOD_5 (Equation 1).

Equation 4-2: BOD_5 calculation

$$\mathrm{BOD}_5\ mg/l = \frac{D_1 - D_2}{P}$$

Where:

D_1 = DO of the diluted sample immediately after preparation, mg/L

D_2 = DO of the diluted sample after five days of incubation at 20 °C, mg/L

P = Decimal volumetric fraction of sample used

Appendix 4-4: Determination of COD

Determination of COD

The closed reflux colourimetric method determined COD (5220 D, APHA, 2017). Digestion solution (1.5 ml) (Appendix 4-8) and Sulphuric reagent (3.5 ml, Appendix 4-8) were added to a portion of the (2.5 ml) sample in the vessel. At 150 °C, the mixture was allowed to digest for 2 hours. The distilled water (reagent blank) and standards (50 ppm, 250 ppm, 500 ppm) were titrated in the same way, ensuring that the total volume of each reaction vessel was the same. The standards were prepared with a stock solution of potassium hydrogen phthalate (KHP) Appendix (4-8). The COD concentration was calculated using the standards calibration curve.

Appendix 4-5: Determination of TSS

Determination of TSS

The gravimetric method (2540 D), (APHA, 2017) determined the TSS. A portion of the sample was filtered through a conventional glass-fibre filter with 70 mm filter paper. After that, the filter residue was dried to a consistent weight in a 105 °C oven and cooled in a desiccator. Total suspended particles are represented by the weight increase of the dried filter paper with residue relative to the weight of the empty filter paper. Total suspended solids were calculated according to Equation 2.

Equation 4-3: TSS Calculation

$$TSS\ (mg/l) = \frac{(A-B)\times 1000\times 1000}{V}$$

Where:

A = Weight of Aluminium dish + filter +dried residue, g

B = Weight of Aluminium dish + filter, g

V = Volume of sample filtered in ml

Appendix 4-6: Determination of Phosphate as Phosphorous

Determination of Phosphate as Phosphorous

The Ascorbic Acid Method determined phosphorus (4500– P E, APHA, 2017). The Persulfate Digestion Method (4500-P B.5) was used to determine the total phosphorous concentration (TP), followed by the Ascorbic Acid Method (4500-P E) as specified by APHA (2017). After thoroughly mixing, a 50 ml sample fixed in situ was pipetted out of the Erlenmeyer flask, then Sulfuric acid (1 ml) (Appendix 4-8) and solid potassium persulfate (0.5 g) were added. The solution was then gently warmed on a preheated hotplate until it reached a final volume of 10 ml. The sample was chilled to room temperature before being diluted to 30 ml with distilled water and the addition of the Phenolphthalein indicator (0.05 ml). The final volume was adjusted to 100 ml with distilled water after each sample was neutralized with sodium hydroxide (1N).

The 50 ml of neutralized sample was pipetted into a clean, dry Erlenmeyer flask, and 0.05 ml of Phenolphthalein indicator was added. Afterward, Sulfuric acid (5N, Appendix 4-8) was added drop by drop until it reached a pale pink colour. Later, 8 ml of the combined reagent (Appendix 4-8) was added. The sample was adequately mixed and held for 10 minutes to develop the blue colour. At 880 nm, the reagent blank absorbance was measured using a 325 – 1000 mm visible Spectrophotometer (CECIL/Model: CE 1011) with the reagent blank as the reference solution.

Standard phosphate solution, which was created using stock phosphate solution (Appendix 4-8), was used to prepare standards (0.25 ppm, 1.0 ppm, and 1.5 ppm). The standards were given the same treatment as the samples.

The absorbance of the standards was plotted against their phosphate concentrations to create a standard curve. The standard curves determined the total dissolved Phosphorous and total Phosphorous concentrations (APHA, 2017).

Appendix 4-7: Determination of TKN

Determination of TKN

The Macro Kjeldahl method (4500-Norg B, APHA 2017) was used to determine the Nitrogen (Organic). The sample (500 ml) was placed into an 800 ml Kjeldahl flask. Borate buffer solution (25 ml) was added, and the sample was adjusted to pH 9.5 using NaOH (6 N) via a pH meter. A few glass beads or boiling chips were added and boiled off the sample. The residue was distilled in a distilling flask and collected the distillate (200 ml) for the titrimetric procedure in a 500 ml Erlenmeyer flask containing indicated boric acid solution (50 ml) (Appendix 4-8). Ammonia in distillate was titrated with standard H_2SO_4 (0.02 N) titrant until the indicator (Appendix 4-8) turned a pale lavender. A blank was carried out for the entire operation and made necessary adjustments to the results. The TKN was calculated according to Equation 3.

Equation 4-4: TKN calculation

$$NH_3 - N/l\ (ml) = \frac{(A-B)\times 280}{Sample, ml}$$

Where:

A = Volume of H_2SO_4 titrated for sample, ml

B = Volume of H_2SO_4 titrated for blank, ml Ammonium

Appendix 4-8: Determination of faecal coliform

Determination of faecal coliform

The calculation of the Bacterial Density test (9221 C) was performed according to APHA guidelines (APHA, 2017) to determine the faecal coliform bacteria. Three sets of five test tubes were taken at first. In each of the first set's test tubes, double-strength MacConkey broth (10 ml) was added. Similarly, single-strength MacConkey broth (10 ml) was poured into the second and third sets of the test tube. After that, Durham's tube was instead inverted into each test tube in each set. Then, all the test tubes were cotton capped and autoclaved for 15 minutes at 15 lb/inc pressure at 121 °C. After chilling, a sample of water is added to each test tube in the following order.

1. Added water sample (10 ml) in each test tube of the first set
2. Added water sample (1 ml) in each test tube of the second set
3. Added water sample (0.1 ml) in each test tube of the third set

Then all set tubes were incubated at 35.5 °C for 24 hours. After incubation, the colour changes of MacConkey broth from red to yellow and gas production in Durham's tubes were observed. Tubes with 10% are dubious. Doubtful test tubes were incubated for another 24 hours to see if gas production had increased. The samples where the gas production remains below 10% are marked as negative and discarded.

Then sterilized the prepared Brilliant Green Lactose Bile broth (BGLB) medium in an autoclave for 15 minutes at 121 °C. Then positive presumptive tubes were shaken gently. Then loopful of culture was transferred into the BGLB fermentation tube. Then, the test tubes were incubated for 48 hours at 35 °C, and then observed the test tubes were for gas production in the BGLB medium. Then according to the results of positive test tubes in three sets, using the published MPN table, the faecal coliform density was calculated.

Appendix 4-9: Preparation of the solutions for physiochemical analysis and bioassay

Preparation of the solutions for Nitrogen determination (organic)

Sodium hydroxide-sodium thiosulfate reagent:

Sodium Hydroxide (NaOH, 500 g) and Sodium Thiosulfate ($Na_2S_2O_3.5H_2O$, 25 g) were dissolved in water and diluted up to 1 L.

Borate buffer solution

Sodium Hydroxide solution (NaOH, 0.1 N, 88 ml) was added to Sodium Tetraborate solution ($Na_2B_4O_7.10H_2O$, 0.025 M, 9.5 g, 500 ml) and diluted up to 1 l.

Dechlorinating reagent

Sodium Thiosulfate ($Na_2S_2O_3.5H_2O$, 3.5 g) was dissolved in water and diluted up to 1 l. 1 ml of reagent was used to remove 1 mg/L residual chlorine from the 500 ml sample.

The absorbent solution, plain boric acid

Boric Acid (H_3BO_3, 20g) was dissolved in water and diluted up to 1 l.

Preparation of the solutions for BOD determination

Alkali-iodide-azide reagent

Sodium Iodide (NaI, 13.5 g) and Sodium Hydroxide (NaOH, 50 g) were dissolved in deionized water. Then the solution was diluted to 100 ml. Sodium Azide (NaN_3, 1g) was dissolved in deionized water (4 ml) and added to the above-diluted solution (100 ml).

Sodium Thiosulphate titrant (0.025 M)

Sodium Thiosulphate ($Na_2S_2O_3$, 6.205 g) was dissolved in deionized water. Then solid Sodium Hydroxide (NaOH, 0.4 g) was added and stirred together to dissolve completely. After dissolving, the entire solution was diluted up to 1 l.

Preparation of the solutions for COD determination

Digestion solution

Potassium Dichromate (10.216 g, previously dried at 150 °C for 2 hours) was dissolved in distilled water (500 ml). Mercuric Sulphate (33.3 g) and Sulphuric acid (167 ml) were added to the solution above, dissolved and allowed to chill to room temperature, and diluted up to 1 l.

KHP solution – 500 ppm

Potassium Phthalate Monobasis ($H_5C_8O_4K$, 0.425 g) was warmed at 110 °C for 30 minutes and dissolved in distilled water (1 l)

H_2SO_4 solution

Conc. Sulphuric acid (2.5 L) was added to silver sulfate (25.3 g) and left behind for 12 hours.

Preparation of the solutions for Phosphate as Phosphorous determination

Sulfuric acid reagent for the digestion

Conc. Sulfuric acid (H_2SO_4, 300 ml) was gently added to distilled water (600 ml) and diluted with distilled water up to 1 l).

Preparation of combined reagent

1. Sulphuric acid (5 N)
   Con. Sulphuric acid (H_2SO_4, 70 ml) was diluted with distilled water up to 500 ml.

2. Antimony Potassium tartrate solution
   Antimony Potassium tartrate solid ($K_2Sb_2S_8H_4O_{12}.3H_2O$, 1.3715 g) was dissolved in distilled water (400 ml) and diluted with distilled water up to 500 ml.

3. Ammonium molybdate solution

   Ammonium molybdate ($(NH_4)_6Mo_7O_{24}$, 20g) was dissolved in distilled water (100 ml)

4. Ascorbic acid solution (0.1 M)

   Ascorbic acid ($C_6H_8O_6$, 1.76 g) was dissolved in distilled water (100 ml)

The combined reagent (100 ml) was prepared by mixing the solutions (1 to 4) accordingly following order and volumes.

1. Sulphuric acid (50 ml)
2. Antimony Potassium tartrate solution (5 ml)
3. Ammonium molybdate solution (15 ml)
4. Ascorbic acid solution (30 ml)

<u>Preparation of Phosphate solutions for the construction of the standard curve</u>

1. Stock Phosphate solution (50 mg/L)

   Anhydrous Monopotassium Phosphate (KH2PO4, 219.5 mg) was dissolved and diluted with distilled water up to 1 L.

2. Standard Phosphate solution (2.5 mg/L)

   A portion of the prepared stock phosphate solution (50 ml) was taken and diluted with distilled water up to 1 L.