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Development and Analysis of a Biomass-Based Cartridge for Textile Wastewater Treatment

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ABSTRACT

Cartridge filter medium are characterized by their multiple layer structures. Three main parameters indicate the filtration performance of the filter medium: initial pressure drop, dust loading characteristics and particle collection efficiency. In this work, samples of textile wastewater are fed into a filter cartridge medium to evaluate the effect of a suitable Biomass material on filtration performance. A pressure gradient of 7.46 psi across a filter Cartridge was evaluated from the analysis of this work. This result indicate a slow increase in pressure drop due to uniformly distributed particles loading inside the cartridge medium. The medium combines a bulky upstream layer and a final layer of high collection efficiency, giving both satisfactory filtration performance values. The analysis of the treated waste fluid also showed a drop in its pH value from 8.8 to 8.0, and its colour intensity from 0.205 to 0.056. The analysis of the ions present in the unfiltered and filtered wastewater, shows a marked drop in the toxic concentration of metallic ions like Chromium, Nickel and Copper from 9.30, 8.00 and 15.00mg/litre to 1.10, 1.45 and 5.00mg/litre respectively. The non-metallic ions concentration like the Sulphate and Chloride ions dropped from 6.32 and 3.96mg/litre to 0.81 and 0.59mg/litre respectively. The equation derived suggest that only properties of the cartridge on which the pressure gradient depend are its specific surface area and its voidage. However, the structure of the cartridge depends additionally on the particle size distribution, the shape and the way the cartridge has been developed.

Keywords: *Biomass-Based, Cartridge, Textile, Wastewater, Treatment.*

1.0. Introduction

Textile wastewater is a highly complex effluent containing a wide range of chemical and physical pollutants that originate from various stages of textile processing. It is typically characterized by elevated Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), which result from the discharge of substantial organic pollutants into the wastewater stream. A notable feature of textile effluent is its intense coloration caused by dyes and pigments that reduce light penetration in receiving water bodies and alter aquatic ecosystems (Wang et al., 2015). The wastewater may also exhibit extreme pH levels, either acidic or alkaline, depending on the specific processing operations involved. Additionally, textile effluent commonly contains high concentrations of Total Suspended Solids (TSS) and Total Dissolved Solids (TDS), mainly due to fibres, dye residues, salts, and other chemical additives used during production (Holkar et al., 2016).

The composition of textile wastewater reflects a diverse array of harmful substances. Synthetic dyes and pigments, many of which are toxic or carcinogenic, are frequently present in significant amounts. Heavy metals such as chromium, copper, and lead may also be found as a result of the use of metal-based dyes and chemical mordants (Carlos et al., 2024). Furthermore, surfactants and detergents applied during washing and scouring processes contribute to foaming and may adversely affect aquatic organisms. The wastewater also carries fibres and other suspended solids that can physically damage aquatic life or disrupt natural habitats (Reno et al., 2022).

The environmental impacts associated with textile wastewater are substantial. Contamination of surface and groundwater resources is common, posing risks to aquatic ecosystems and human health. Soil quality may also deteriorate when such wastewater infiltrates the ground, leading to reduced fertility and disruptions in plant growth (Qasim, 1999). In addition to water and soil pollution, textile operations can contribute to air pollution through the release of volatile organic compounds and other airborne contaminants during processing (Hussain and Wahab, 2018).

Despite these challenges, effective textile wastewater treatment and management offer significant economic and environmental benefits. Proper treatment promotes water conservation, reduces operational costs, supports compliance with environmental regulations, and contributes to broader goals of sustainable development.

Textile Wastewater poses a significant environmental health risk due to its complex composition, including multiple dyes, organic and inorganic salts and toxic effluents. Controlling this effluent is crucial for the economy and environmental protection (Bayramoglu et al, 2017). Water filtration remains a crucial aspect for efficient wastewater management. Modern domestic appliances equipped with internal filtration systems have driven innovation in water filtration technology (Bankole and Adekunle, 2018). Among various water treatment techniques, filtration stands out (Muhammad and Lee, 2019). However, research on sediment layers Cartridge filter hydraulic analysis is scarce. This brings the novelty of developing a filter cartridge compacted with Biomass and other materials which has the tendency to absorb toxic ions from waste fluids (Evangelista et al, 2019) Existing studies focus on water quality, (Wahab et al, 2022) filtration efficiency, or specific substance removal (Mujumdar and Sinha, 2021). This study investigates the impact of cartridge filter installation (Li et al, 2022), on head losses in wastewater treatment plants (Murat et al, 2017). These effects significantly influences pressure values, affecting electromechanical elements performance.

A cartridge filter is a type of filtration system that uses a replaceable cartridge or element to remove impurities or contaminants from fluids, such as water, air or other liquids (Afkhami et al, 2019). The Cartridge typically contains a filtering medium, such as activated carbon, membranes, or fibres that captures particles, chemicals, or other impurities as the fluid passes through. Examples of Cartridge Filters includes, Water Filter Cartridges, Air Filter Cartridges, Industrial Filter Cartridges, Oil Filter Cartridges, Membrane Filter Cartridges and Sediment Filter Cartridges (Cheng, 2019).

The benefits of a Cartridge filter includes easy maintenance, a high efficiency in capturing very small particles and impurities, flexibility in its wide range of applications and cost effectiveness.

Sediment Cartridge filters are modular, simple and effective cartridge for removing particles and chemicals from water. Materials used for its development includes, Polypropylene, Biomass and other materials. These have the tendency to remove solid particles greater than one micron meter, and various other toxic ions like Chromium, Nickel, Copper, Zinc, Cadmium, Lead, Cobalt, Antimony, Sulphate, Chloride and Sodium from waste fluid (Deena and Selvaraj, 2019)

The concentrations of these ions can vary depending on the textile industry's production processes and wastewater treatment efficiency. Exposure to these toxic ions can harm human health and the environment, emphasizing the need for effective wastewater treatment and management strategies. Overall, textile wastewater management is crucial for protecting the environment, conserving water resources, and promoting sustainable development in the textile industry.

This study aims to derive an optimized model expression of a cartridge filter packed with Biomass and other materials in relation to a drop in pressure per unit length of the cartridge for a flowing fluid stream (Textile Wastewater). The study also aims at carrying out a qualitative and quantitative analysis check on the filtered and unfiltered textile wastewater with respect to its ionic concentrations to analyze its level of toxicity before and after its treatment (Ojokuku, 2019)

2.0 Methodology

Various Biomass and other materials like, Water hyacinth, Moringa seeds, Glass fibres, Polypropylene, Polyester cellulose and Wool fibre are utilized as layers sediment within a cartridge column, as schematically shown in figure 1.

Each of the materials were analyzed at the Kano Education Research Development Council (KERDC) laboratory to determine their porosity and the pore space diameter, and the density of the textile wastewater from African Textile Mills Limited, Challawa, Kano State.

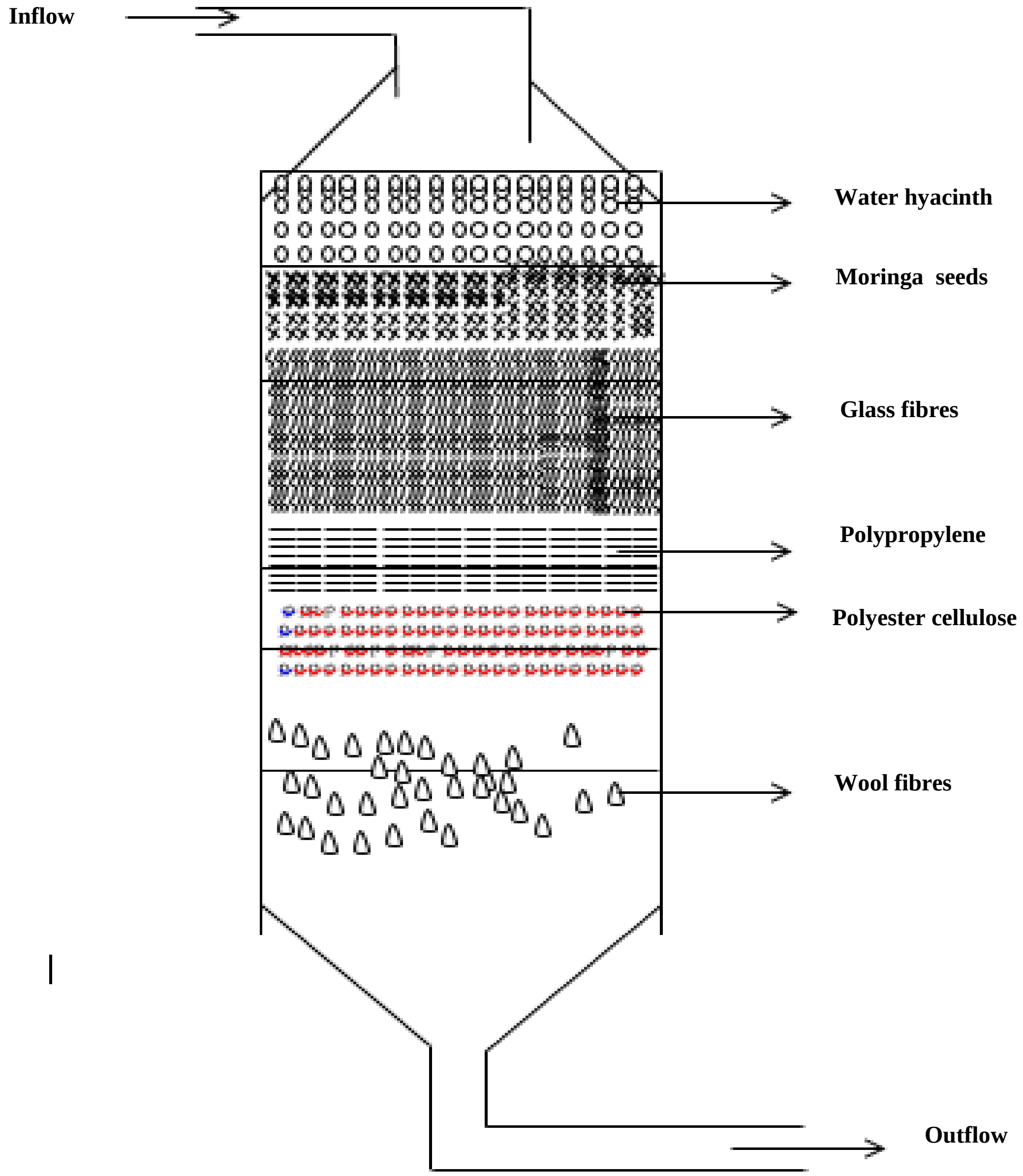

Figure 1: Cartridge Column

The cartridge made of Polyvinyl Chloride (PVC) plastics, with an input and output column packed with biomass and other feedstock. Raw textile wastewater was subjected to filtration through the cartridge.
The point of inflow and outflow was fitted with a gauge to monitor the differential pressure drop. This is between the point at which the wastewater enters the cartridge and the point at which it exits the cartridge (Lofrano and Brown, 2010).

Considering factors like -△P = Pressure drop in pounds per square inch (Psi), L= length of cartridge, ℓ = Voidage (porosity), μ = Viscosity of waste fluid, ρ = Density of waste fluid, Uc = Average fluid flow velocity, d = Diameter of pore space in micron meter (μm), for all the materials in the cartridge.
The Ergun model equation (Coulson and Richardson, 2019) which expresses the friction factor in a packed column as a function of the modified Reynolds number, was employed to determine the pressure drop across the cartridge filter.
Employing the equation
For flow (streamline and turbulent) through ring packing's, Ergun (Coulson and Richardson, 2019) obtained a good semi-empirical correlation for pressure drop as follows.

$$\frac{-\Delta P}{L} = \frac{150(1-\ell)^2}{\ell^3}\frac{\mu Uc}{d^2} + \frac{1.75(1-\ell)}{\ell^3}\frac{\rho Uc^2}{d} \quad (1)$$

Considering S = Surface area per unit volume
S_B = Surface area presented to the fluid per unit volume of the cartridge.
S and S_B are not equal due to the voidage occurring when the particles are packed in a cartridge. If point contact occurs between the particles so that only a very small fraction of surface area is lost by overlapping.

Then $S_B = S(1-\ell)$ (2)

S is the specific surface area of the particles divided by its volume, with unit, (length)$^{-1}$. For a typical spherical particle.

$$S = \frac{4\pi R^2}{4/_3 \pi R^3} \quad (3)$$

Where R= Particles radius.

From equation (3)

$$S = \frac{3R^2}{R^3} \quad (4)$$

Considering the particle diameter $d = 2R$

Hence $R = \frac{d}{2}$ (5)

$$S = \frac{3(d/_2)^2}{(d/_2)^3} \quad (6)$$

$$S = \frac{3}{d/_2} \quad (7)$$

$$S = \frac{6}{d} \quad (8)$$

$$d = \frac{6}{S} \quad (9)$$

For the above expression to be generally useful, an expression is needed for an equivalent diameter of the pore channels d_m

d_m Could be taken as

$$d_m = \frac{\ell}{S_B} = \frac{\text{Volume of void filled with fluid}}{\text{Wetted surface area of the bed}}$$

$$d_m = \frac{\ell}{S(1-\ell)} \quad (10)$$

In a cube of side X, the volume of free space is ℓX^3, so that the mean cross-sectional area for flow is the free volume divided by the height, or ℓX^2. The volume flowrate through this cube is $U_C X^2$, so that average linear velocity through the pores, U_1 is given by

$$U_1 = \frac{U_C X^2}{\ell X^2} = \frac{U_C}{\ell} \tag{11}$$

Putting $d = \frac{6}{S}$ in equation (1)

$$\frac{-\Delta P}{L} = \frac{150(1-\ell)^2}{\ell^3} \frac{\mu U_C S^2}{6^2} + \frac{1.75(1-\ell)}{\ell^3} \frac{\rho U_C{}^2 S}{6} \tag{12}$$

$$\frac{-\Delta P}{L} = \frac{(1-\ell) U_C S}{6\ell^3} \langle \frac{150(1-\ell)\mu S}{6} + \frac{1.75\rho U_C}{1} \rangle \tag{13}$$

$$\frac{-\Delta P 6\ell^3}{L(1-\ell) U_C S} = \langle \frac{150(1-\ell)\mu S}{6} + \frac{1.75\rho U_C}{1} \rangle \tag{14}$$

$$\frac{-\Delta P 6\ell^3}{L(1-\ell) U_C S} = \langle 25(1-\ell)\mu S + 1.75\rho U_C \rangle \tag{15}$$

$$\frac{-\Delta P 6\ell^3}{L U_C S} = \frac{\ell^3}{(1-\ell)} = \langle \frac{25(1-\ell)\mu S}{6} + \frac{1.75\rho U_C}{6} \rangle \tag{16}$$

$$\frac{-\Delta P 6\ell^3}{L U_C S} \times \frac{\ell^3}{(1-\ell)} = 4.17(1-\ell)\mu S + 0.29\rho U_C \tag{17}$$

Dividing through by ρUc

$$\frac{-\Delta P}{L U_C S} \times \frac{\ell^3}{(1-\ell)} \times \frac{1}{\rho U_C} = \frac{4.17(1-\ell)\mu S}{\rho U_C} + \frac{0.29\rho U_C}{\rho U_C} \tag{18}$$

$$\frac{-\Delta P}{L U_C{}^2 S} \times \frac{\ell^3}{(1-\ell)} = \frac{4.17(1-\ell)\mu S}{\rho U_C} + 0.29 \tag{19}$$

Considering $\frac{\rho U_C d_m}{\mu}$ = Reynolds number (Re)

$$Re = \frac{U_C}{\ell} \times \frac{\ell}{S(1-\ell)} \times \frac{\rho}{\mu} \tag{20}$$

$$Re = \frac{U_C \rho}{S(1-\ell)\mu} \tag{21}$$

Then $Re^{-1} = \frac{S(1-\ell)\mu}{U_C \rho}$ (22)

Similarly equation (22) becomes

$$\frac{-\Delta P}{L U_C S} \times \frac{\ell^3}{(1-\ell)} = 4.17 Re^{-1} + 0.29 \tag{23}$$

$$\frac{-\Delta P \ell^2 d_m}{L U_C \rho} = 4.17 Re^{-1} + 0.29 \tag{24}$$

$$\frac{-\Delta P}{L} = \frac{\rho U_C}{\ell^2 d_m} (4.17 Re^{-1} + 0.29) \tag{25}$$

Equation (25) can be used to determine the pressure drop per unit length across the cartridge filter.

Table 1:Qualitative and Quantitative Analysis for the Wastewater Fluid

Ion	Qualitative Analysis	Quantitative Analysis
Nickel	Dimethylglyoxime (DMG) Test: Add DMG solution to the wastewater sample. A pink or red precipitate forms if Nickel is present.	Atomic Absorption Spectroscopy (AAS): AAS measures the absorption of light by Nickel atoms at a specific wavelength
Chromium	Diphenylcarbazide method: This method involves reacting Chromium ions with Diphenylcarbazide to form a coloured complex, which can be detected spectrophotometrically.	Atomic Absorption Spectroscopy (AAS): AAS can detect Chromium ions in the range of 0.01-26mg/l
Sulphate	Sulphate ions can be detected through a precipitation reaction with Barium Chloride. This forms a white precipitaie of Barium Sulphate. This reaction is a clear indication of the presence of Sulphate ions.	Spectrophotometry: This method measures the absorbence of light by the sulphate ions or their complexies.
Chloride	One method of qualitative analysis of Chloride ions involves the use of Silver Nitrate. When Silver Nitrate is added to a sample containing Chloride ions, a white precipitate of Silver Chloride is formed.	Ion Exchange Method: Fhis method involves exchanging Chloride ions with other ions on a resin, and allowing the determination of Chloride concentration.
Copper	UV-VIS Spectometry:Copper ions can be converted to coloured complexies and detected using UV-VIS Spectometry, providing a qualitative indication of their presence.	Atomic Absorption Spectrophotometry (AAS). A widely used method for analysing the concentration of copper ions in wastewater.
Cadmium	Thin Layer Chromatography (TLC): A simple and rapid proceedure for screening Cadmium ions in textile wastewater.	Inductively Coupled Plasma Mass Spectrometry (ICP-MS). A highly sensitive method for detecting Cadmium ions in textile wastewater, suitable for concentration greater than 100mg/kg.
Lead	Calometric Method: This method uses specific reagents to form a coloured complexes with lead ions, allowing visual detection. For example, dithizone can be used to form a pink-coloured complex with Lead ions.	Atomic Absorption Spectroscopy (AAS). This can detect Lead ions at very low concentrations, and its suitable for both flame and graphite furnace modes.
Cobalt	Thiocyanate Test: Cobalt ions react with Thiocyanate ions to form a blue coloured complex, indicating the presence of Cobalt.	Atomic Absorption Specttometry (AAS): This method involves pre-concentration of Cobalt ions using dispersive liquid-liquid micro-extraction (DLLME) or solid phase extraction (SPE) followed by AAS measurement. The detection limit for cobalt using this method is around 0.7mg/litre
Antimony	Supramolecular Solvent-Based Liquid-Liquid Extraction: This method involves te use of Supramolecular solvents for the extraction of antimony ions, which can be detected using Spectrophometry.	Graphite Furnace Atomic Absorption Spectrometry (GFAAS): This method is used for determining antimony ions in water samples with detection limit of 0.01mg/litre
Zinc	Calometric Detection: A paper-based analytical device is used for Zinc ion quantification, utilizing a calometric indicator like zinc ion. This method provides a simple and rapid detection of zinc ions.	Atomic Absorption Spectroscopy (AAS) is the common method applicab;le to determine the concentration of zinc ions in wastewater.

3.0 Results and Discussion

4.1 Pressure Drop Analysis Across the Cartridge Filter

The results of the analysis prior to the inflow, and the outflow of the wastewater in the cartridge filter are shown in table 1 below. From the derived model equation 25, the average pressure drop per unit length of the cartridge filter is calculated from Table 2.

Table 2: Pressure drop per unit length across the cartridge filter

Material	ℓ	$(1-\ell)$	d (μm)	$S={}^{6}/_{d}$	$S_B = S(1-\ell)$	$dm = \ell/S_B$	$-\Delta P/_L$ (Psi)
Water hyacinth	0.697	0.303	0.58	10.34	3.133	0.222	0.001
Moringa seed	0.323	0.677	0.34	17.05	11.949	0.027	0.039
Glass fibre	0.04	0.960	6.50	0.93	0.892	0.045	1.50
Polypropylene	0.005	0.995	120	0.05	0.05	0.100	43.20
Polyester cellulose	0.99	0.010	25.0	0.24	0.002	49.5	$2.23\text{x}10^{-7}$
Wool fibre	0.088	0.912	20.06	0.29	0.264	0.333	0.042

The structural properties of the various filter materials and their corresponding pressure drops per unit length are presented in Table 2. The results show wide variations in porosity, specific surface area, and resistance to flow.

Materials such as polypropylene exhibited the highest pressure drop (43.20 psi), mainly due to its extremely low porosity (l = 0.005), which restricts wastewater movement and increases hydraulic resistance. Glass fibre also demonstrated a relatively high pressure drop (1.50 psi), attributed to its dense structural composition.

In contrast, water hyacinth produced the lowest pressure drop (0.001 psi), indicating that its fibre structure allows easier fluid passage. Polyester cellulose, despite having a very high porosity (l = 0.99), recorded a near-zero pressure drop because of its large pore volume and low surface resistance.

Using a wastewater density of 1.854×10^{-3} kg/m³ and a flow velocity of 0.2 m/s, which corresponds to a turbulent regime (Re ≈ 3500), an average pressure drop of 7.46 psi across the cartridge length was obtained. This indicates that the overall filter configuration can sustain the hydraulic load under industrial operating conditions.

Table 3: Analysis and result of the raw and treated wastewater from the cartridge filter

Characteristics	Inflow	Outflow
Point of Hydrogen Scale (pH)	8.8	8.0
Chemical Oxygen Demand (COD) (mg/L)	3440	2400
Biological Oxygen Demand (BOD) (mg/L)	2260	560
Total Solid (TS) (mg/L)	2280	51
Suspended Solid (SS) (mg/L)	385	120
Total Dissolved Solid (TDS) (mg/L)	2720	700
Turbidity (NTU)	41.65	27.8
Temperature (^{0}C)	44	39
Colour	0.205	0.051

NTU: Nephelmometric Turbidity Units
mg/L: Milligram per Litre

4.2 Physicochemical Characteristics of Raw and Treated Wastewater

The effects of filtration on the physicochemical quality of wastewater are shown in Table 3. Substantial improvements were recorded after passing through the cartridge filter. COD reduced from 3440 mg/L to 2400 mg/L (30.2% removal), while BOD dropped sharply from 2260 mg/L to 560 mg/L (75.2% removal). The higher BOD removal indicates that biodegradable organic matter was effectively captured by the fibrous filter media.

Total solids decreased drastically from 2280 mg/L to 51 mg/L (over 97% removal). Suspended solids also reduced significantly (385 mg/L to 120 mg/L), and dissolved solids reduced from 2720 mg/L to 700 mg/L, confirming the filter's ability to remove both particulate and dissolved impurities.

Turbidity reduced from 41.65 NTU to 27.8 NTU, reflecting improved clarity. Colour intensity decreased from 0.205 to 0.051, showing retention of pigment molecules. Temperature reduced slightly from 44°C to 39°C, likely due to heat loss during filtration.

The wastewater pH reduced from 8.8 to 8.0, indicating a mild neutralising effect possibly from adsorption reactions in the filter media.

4.3 Ionic Concentration Reduction

Table 4: Ionic Concentrations of the Raw and Treated Wastewater from the Cartridge filter

Ions	Unfiltered mg/l	Filtered mg/l
Chromium (Cr)	9.3	1.1
Nickel (Ni)	8	1.45
Copper (Cu)	15	5
Cadmium (Cd)	0.55	0.15
Lead (Pb)	0.21	0.1
Cobalt (Co)	4.27	1.25
Antimony (Sb)	0.48	0.15
Zinc (Zn)	3.52	2.61
Sulphate	6.32	0.81
Chloride	3.69	0.59

The ionic analysis of the raw and treated wastewater in Table 4 revealed significant reductions in the concentrations of heavy metals and anions after filtration through the cartridge system. Chromium concentration decreased markedly from 9.3 mg/L in the unfiltered wastewater to 1.1 mg/L after treatment, demonstrating strong removal efficiency. Nickel also showed substantial improvement, reducing from 8 mg/L to 1.45 mg/L. Copper levels declined from 15 mg/L in the raw wastewater to 5 mg/L following filtration, while cadmium showed a notable drop from 0.55 mg/L to 0.15 mg/L. Lead concentration was reduced from 0.21 mg/L to 0.10 mg/L, and cobalt decreased from 4.27 mg/L to 1.25 mg/L, indicating effective adsorption of these metals by the filter media. A similar trend was observed for antimony, which fell from 0.48 mg/L to 0.15 mg/L after treatment. Zinc showed a smaller yet appreciable reduction from 3.52 mg/L to 2.61 mg/L.

In addition to heavy metals, the cartridge filter also significantly reduced anionic concentrations. Sulphate levels dropped from 6.32 mg/L in the untreated wastewater to 0.81 mg/L after filtration, while chloride decreased from 3.69 mg/L to 0.59 mg/L. These results collectively show that the cartridge filter effectively removes both heavy metals and inorganic ions, thereby improving the overall chemical quality of the wastewater.

4.0 Conclusion

This study has demonstrated the effectiveness of a fibre-based cartridge filtration system in significantly improving the physicochemical and ionic quality of textile wastewater. The evaluation of the pressure drop across different filter materials showed that, although the hydraulic resistance varied widely, the overall average pressure drop of 7.46 psi indicates that the system can operate efficiently under industrial flow conditions without imposing excessive energy demands. Materials such as water hyacinth and polyester cellulose exhibited excellent permeability, while polypropylene and glass fibre presented higher resistance but enhanced filtration density.

The performance assessment of the cartridge filter revealed substantial improvements across key water quality indicators. Organic pollutants, represented by COD and BOD, recorded remarkable reductions, with BOD showing over 75% removal efficiency. Solid content, including total solids, suspended solids and dissolved solids, was drastically reduced, indicating effective physical entrapment and adsorption within the filter matrix. The reduction in turbidity and colour further confirms the filter's ability to remove colloidal and dye-based contaminants typically associated with textile wastewater. Changes in pH and temperature also showed a trend toward more stable effluent characteristics suitable for downstream discharge or secondary treatment.

Heavy metal and ionic analysis showed that the cartridge filter achieved high removal efficiencies for most toxic metals such as chromium, cadmium, nickel and cobalt, and also significantly reduced key anions including sulphate and chloride. These reductions suggest strong ion-binding interactions and adsorption mechanisms within the composite filter media.

The results establish that the cartridge filter system is a viable and efficient technology for primary and intermediate treatment of textile wastewater. Its ability to reduce organic load, solids, turbidity, colour, heavy metals and inorganic ions makes it a promising option for improving effluent quality before final discharge or secondary treatment. The findings further highlight the potential for using locally available fibrous materials, such as water hyacinth and moringa seed, to develop cost-effective and environmentally friendly filtration solutions for industrial wastewater management.

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