Investigation of Pearl Millet Stacks and Polyurethane Foam as Packing Material for the Removal of Volatile Organic Compounds from Tannery Effluent through Biofiltration for Environmental Application

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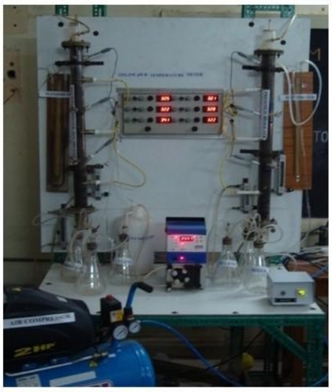
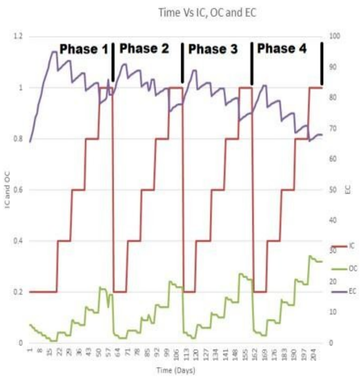
Abstract

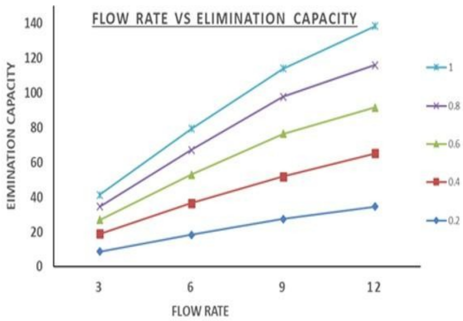
The leather tanning industry plays an important role in the economy, is a significant source of environmental pollution due to the release of volatile organic compounds (VOCs) such as benzene, toluene, xylene (BTX) in addition to other chemicals. This study focuses on the feasibility of using pearl millet stacks, a sustainable and locally available agricultural by-product, polyurethane foam and the mixture of the above in 1:1 ratio as packing materials in a biofiltration process and examine their removal efficiency towards certain VOCs from tannery effluent. A custom-built-up flow biofilter is studied with microorganism inoculated packing material to evaluate the removal efficiency and elimination capacity under varying flow rates, inlet VOC concentrations and operational durations. The results show that pearl millet stacks exhibit superior removal efficiency (up to 95%) compared to polyurethane foam and the mixed bed. The removal efficiency reaches the maximum after 15–16 days of operation, which indicates the critical role of microbial acclimatization. The efficiency is observed to differ at various flow rate of the effluent, inlet loading rate (ILR). The results obtained demonstrates pearl millet stack as the promising biofilter bed for the effective removal of VOCs from tannery effluent.

Graphical Abstract


Biofiltration



Flow rate in different phases



Flowrate Vs elimination capacity

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1.0 Introduction

Animal's skin and hides are chemically treated with several harmful toxic chemicals to make them suitable for leather production (Malabad et al. 2025). This process, known as leather tanning, makes it difficult for the bacteria and the fungus to break down the biomaterial of the skin. Thus, unusable animal hide is processed into useful leather which is further used to make several leather articles (Thomasset Benayoun, 2024). Among the several tanning methods, chrome tanning is the most preferred process as it is quick, inexpensive; produce soft yet strong leather which can retain colour for its entire life span (Amalia et al., 2026).Though heavy metals such as Cr (III) are dangerous pollutants in the tannery effluent, the volatile organic compounds (VOCs) cannot be neglected as they can cause respiratory issues and damage liver, kidneys, etc. in human. Also, they pollute the atmosphere by contributing to the greenhouse effect and global warming (Alemu et al., 2024).

VOCs, organic chemicals with low boiling point are used in large quantity as solvent almost at all the stages of the leather tanning such as soaking, drying, fat liquoring, finishing etc, shown in **Table 1**. Several volatile low boiling solvents are employed for the tanning. Some of them are acetone, cyclohexanone, methyl ethyl ketone, ethyl acetate, xylene, benzene, toluene, etc (Maki et al., 2025). Most of them with low boiling point readily escape from the effluent to the atmosphere when they are discharged from the industry. This study focuses on aromatic hydrocarbons xylene, benzene and toluene termed as BTX here after, which have relatively higher boiling point, **Figure 1**.

Table 1: Common volatile organic compounds with boiling points

Sl. No	Volatile Organic compound	Functional group	Boiling point (^oC)
1	Acetone	Ketone	56
2	Petroleum ether	Aliphatic hydrocarbon	60-95
3	Diethyl ether	Ether	34.6
4	Chloroform	Aliphatic halogen	61.2
5	Dichloromethane	Aliphatic halogen	39.6
6	Benzene	Aromatic hydrocarbon	80.1
7	Toluene	Aromatic hydrocarbon	110.6
8	Xylene	Aromatic hydrocarbon	138-144
9	Ethyl acetate	Ester	77.1
10	Tetrahydrofuran	Ether	66
11	Pentane	Aliphatic hydrocarbon	36.1
12	Hexane	Aliphatic hydrocarbon	68.7
13	Ethyl methyl ketone	ketone	79.6
14	Cyclohexanone	ketone	155.6

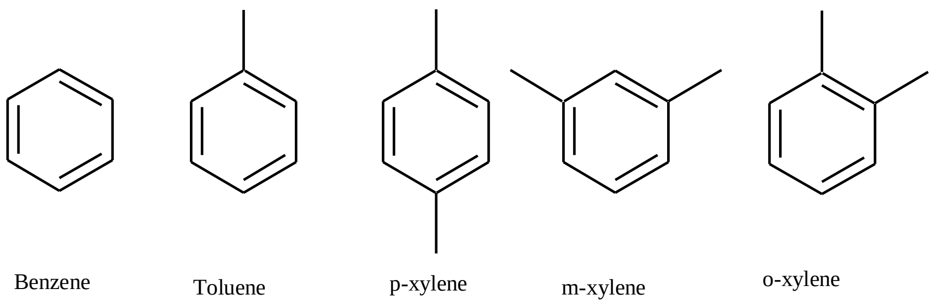

Figure 1: Structure of aromatic VOCs

The use of aromatic solvents in leather tanning and finishing is important because they are used to dissolve oils, waxes, dyes and other hydrophobic materials which are required to be removed or spread in the process (Zhang et al., 2025). Xylene mixtures are used in the tanning industry to remove the wax and fat materials, toluene in the dyeing process as it is able to dissolve dyes well and benzene has been used in the finishing stage to dissolve aniline dyes (Horva et al., 2025). They have been extensively used in leather operation because they help to improve penetration, uniformity and surface finish. They are also volatile organic compounds; if not controlled, however, they may cause air pollution and exposure hazards to workers (Chen et al., 2025). For this reason, many modern leather processes try to minimize the use of solvents, improve ventilation and eliminate as many as possible the use of undesirable aromatic solvents for the use of others less harmful. The main association with xylenes is for degreasing and wax removal, to prepare the hide for subsequent chemical treatment (Rahmawati et al., 2025). One main advantage of using toluene in leather dyeing is its ability to dissolve and transport the dyes more evenly throughout the leather matrix. The use of benzene has been severely restricted in most applications due to its toxic and carcinogenic properties that were once used in finishing (Patra & Pariti, 2022). Aromatic solvents, in general, have importance in leather processing industries as their strong dissolving power but their usage should be controlled taking into account environmental and health related issues (de Oliveira et al., 2025). The industry is shifting toward less solvent and more environmentally friendly systems for a safer and more sustainable tanning. Further, BTX concentration will be relatively high compared to other tanning agents as they are used as solvents for the removal of wax material, finishing, dying, etc., shown in **Table 2**.

Table 2: Role of aromatic solvents in leather tanning Process

Sl. No	VOC	Process	Role
1	Mixture of xylenes	Removal of wax and fat material	solvent
2	Toluene	Dying	Solvent, Dissolves dyes
3	Benzene	Finishing	Solvent, Dissolves aniline based dyes

Organic pollutants in the tannery effluent is a major concern for the environment as they are toxic and lead to enhanced greenhouse effect (Sarker et al., 2026). Further, hydrocarbons are not readily digested by the microorganisms present in the water or soil. Chlorinated solvents may even lead to ozone layer depletion in addition to greenhouse effect. Several methods and processes have been established to remove the organic pollutants and waste from the effluent, **Figure 2**. Though strict measures are taken to remove the organic pollutants during the effluent treatment stage, considerable quantity of organic pollutants is generally discarded (Pundir et al., 2025; Li et al., 2025). So there is an existing need for purification of industrial waste water, particularly tannery effluent, at various level of the water treatment, so that it could be safely discharged into the water bodies. This research work focuses on employing readily accessible packing material for the biofiltration process and evaluating the elimination capacity of volatile organic compounds specifically benzene, toluene and xylene at variable parameters like flow rate, time and concentration of VOCs. Also, this article aims at comparing the effect of natural and synthetic packing material on the elimination capacity.

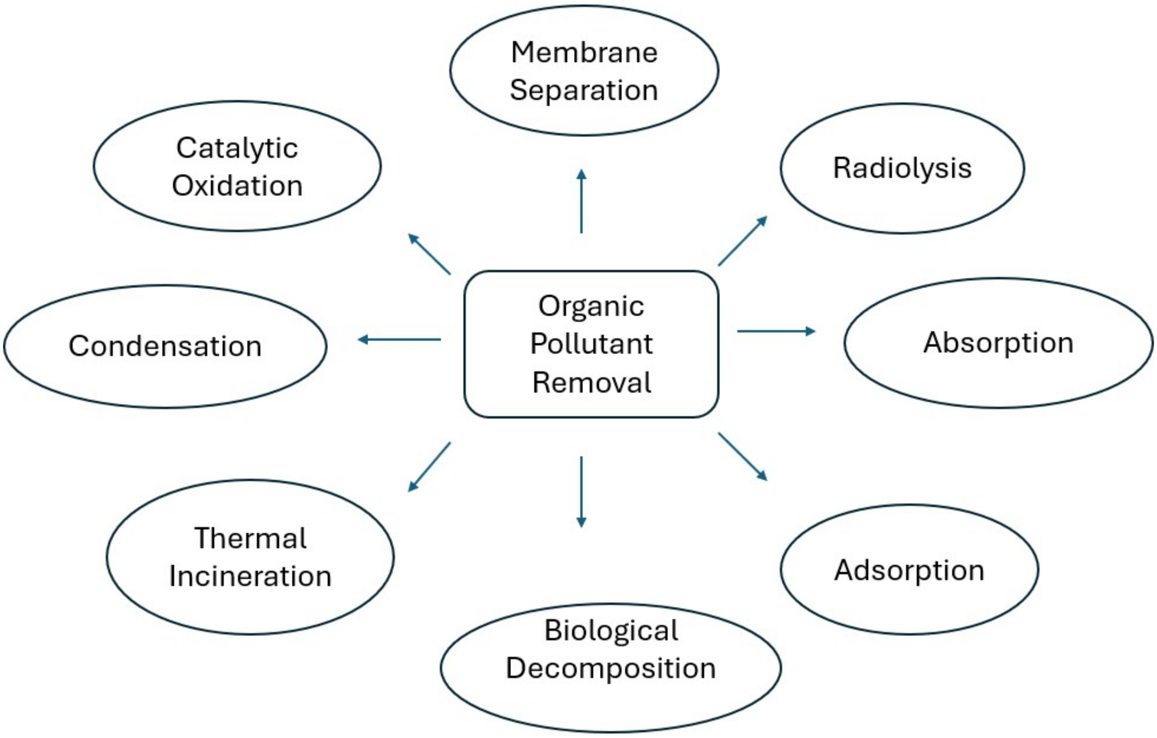

Figure 2: Organic pollutants removal techniques

1.1 Biofiltration

One of the most promising methods to remove organic pollutant is biofiltration.[8] In this biological process the effluent is passed through a biofilter reactor, a packing material bed inoculated with microorganisms, during which the organic compounds ($C_xH_yO_z$) gets decomposed to produce CO_2, water and heat energy, as shown in Equation 1. The microorganism adheres to the pores present in the packing material and multiply when provided required nutrients and oxygen.

$$C_xH_yO_z + O_2 \longrightarrow CO_2 + H_2O + \text{Heat} \quad (1)$$

Corn cob, sugar cane bagasse and coconut fibre are the most studied packing material in the biofiltration process due to their porous nature, rigidity and availability (Li et al., 2025; Nayyeri et al., 2022). This research investigates the possibility to use pearl millet stacks, polyurethane foam as packing materials for the biofiltration process.

2.0 Experimental Section

2.1 Collection and Preparation of Packing Materials

The pearl millet stacks were collected from Villupuram district, Tamil Nadu, India during the month of May-June. The stacks were dried in the sun light and the grains were removed without much disturbance to the stacks. The stacks were yellow or light brown in colour after drying and the height was in the range of 13-15 inches. The stacks were cut into pieces across the stacks (approximately 1 cm length) and used for inoculation. Commercially available polyurethane was cut into pieces of 1cc and used (surface area of 1.3–1.6 x 10^5 m^2 m^{-3}). The stored packing materials are cleaned using distilled water and dried in a hot air oven at 80ºC for couple of days, and autoclaved. The choice of selection of packing material is based on the surface area of the packing material, their stability, availability, porous nature, etc. Polyurethane is synthetic organic material and is expected to be relatively stable during the process of biofiltration. Various parameters of pearl millet stack packing material are determined following the standard procedure and tabulated in **Table 3**.

Table 3: Characterization of the pearl millet packing material

Sl. No	Parameters	Pearl millet	Unit
1	Particle size	1.2	cm
2	pH	6.3	-
3	Moisture	65	g
4	Specific gravity	1.35	-
5	Weight (Wet filled)	180	g
6	Weight (Dry filled)	101	g
7	BET surface area	4.146	m^2/g
8	Total pore volume	0.0042	cm^3/g
9	Average pore size	39.14	A°
10	Carbon (%)	43.22	-
11	Hydrogen (%)	2.8	-
12	Nitrogen (%)	0.009	-
13	Sulphur (%)	0.99	-
14	Oxygen (%)	44	-

The following chemicals were used to provide necessary nutrient required for the growth of microbes.[13] K_2HPO_4 - 0.91g; $Na_2HPO_4{\cdot}2H_2O$ - 2.39g; KNO_3 - 2.96g; $(NH_4)_2SO_4$ - 1.97g; $FeSO_4{\cdot}7H_2O$ - 0.2g; $MgSO_4{\cdot}7H_2O$ - 2.0g; $MnSO_4{\cdot}7H_2O$ - 0.88mg; $Na_2MoO_4{\cdot}2H_2O$ - 1mg; $CaCl_2$ - 3 mg; $ZnSO_4{\cdot}7H_2O$ - 0.04 mg; $CoCl_2{\cdot}6H_2O$ - 0.04 mg. Stock solutions were used when the quantity of the nutrient is in a few milligrams.

2.2 Collection and Characterization of Wastewater Samples

Three waste water samples were collected from the common effluent treatment plant from Tanners Industrial Effluent Treatment Company Limited, Pallavaram, Chennai, India on three different days at the interval of 7 days and used as such for the study without any further treatment. The characterization details of effluent samples are given in **Table-4**. The physicochemical parameters provide critical baseline information for assessing the efficiency of subsequent biofiltration process.

Table 4: Characterization of the effluent samples

Sl.No	Parameters	Sample - 1	Sample - 2	Sample - 3	Unit
1	Temperature	27	29	30	ºC

2	pH	8.2	8.1	8.1	-
3	Electrical conductivity	6.32	6.41	6.39	mmho/cm
4	Color	Dark Brown	Dark Brown	Dark Brown	-
5	Total solids	7360	7180	7260	mg/L
6	TDS	4360	4310	4270	mg/L
7	TSS	5100	5280	5020	mg/L
8	COD	1570	1440	1660	mg/L
9	BOD	120	180	140	mg/L
10	Sulphide	280	270	280	mg/L
11	Chromium	7.26	8.2	7.24	mg/L
12	Chloride	1730	1710	1830	mg/L
13	Phenols	30	41	36	mg/L
14	Oil and Grease	100	145	180	mg/L
15	Benzene	1.1	1.15	1.1	g/L
16	Chloroform	0.9	0.92	0.91	g/L
17	Trichloroethylene	1.5	1.51	1.25	g/L
18	Toluene	48	45	49	mg/L
19	Xylene mixture	210	198	210	mg/L
TDS- Total dissolved solids; TSS- Total suspended solids; COD- Chemical oxygen Demand; BOD- Biochemical oxygen Demand					

2.3 Preparation and Inoculation of the Biofilter with Activated Sludge

The activated sludge from paper industry in Sivakasi, Tamil Nadu, India, was used to inoculate the packing material, **Figure 3**. The sludge contains mixed microorganisms and were identified as bacillus sp. and pseudomonas sp. following the response to chemical test. The mixed inoculum is placed in a two-liter conical flask and allowed to settle down for 20 min and then the supernatant liquor is removed. The remaining suspension is used as inoculum. Before addition of packing material in to biofilter, the packing materials are soaked in a nutrient solution to absorb water and nutrients[15].

Figure 3: Photographic view of inoculum used in the biofiltration

2.4 Design and setup of the up flow biofilter system

An up flow mode biofilter is employed in this study. The biofilter consists of two columns. Both columns are 1 m high with an internal diameter of 5cm. The column is made up of acrylic material. A detailed sketch of the complete assembled column is shown in **Figure 4** and photographic view of the biofilter is shown in **Figure 5**. The biofilter column had three sections, bottom (12.5 cm), middle (75 cm) and top (12.5 cm). The bottom section used for the pollutant distribution section, the middle section used for the biofilter and top section is used for the nutrient distribution section. The volume of packing media is 0.00147 m^3. Each column consists of three ports for temperature measurement and three ports for sampling spaced 25 cm apart. The columns are mounted on a table made up of steel angle with metal top and metal bench for mounting conical flask. The additional units are flow meters, manometers, nutrient supply pump, compressor and storage vessel for nutrient.

Samples are collected through the Teflon seal. Both the ends of the columns are closed with acrylic flanges and an airtight seal is achieved by using an O- ring between the column and the flanges. The bolts are used to connect the flanges and the clamping ring is used to provide the effective airtight seal. The top and bottom section has two 0.5 cm ports. Each port is fitted with 0.5cm acrylic tube one for inlet and other for outlet of air. The port in the bottom section is used to drain the excess water from column.

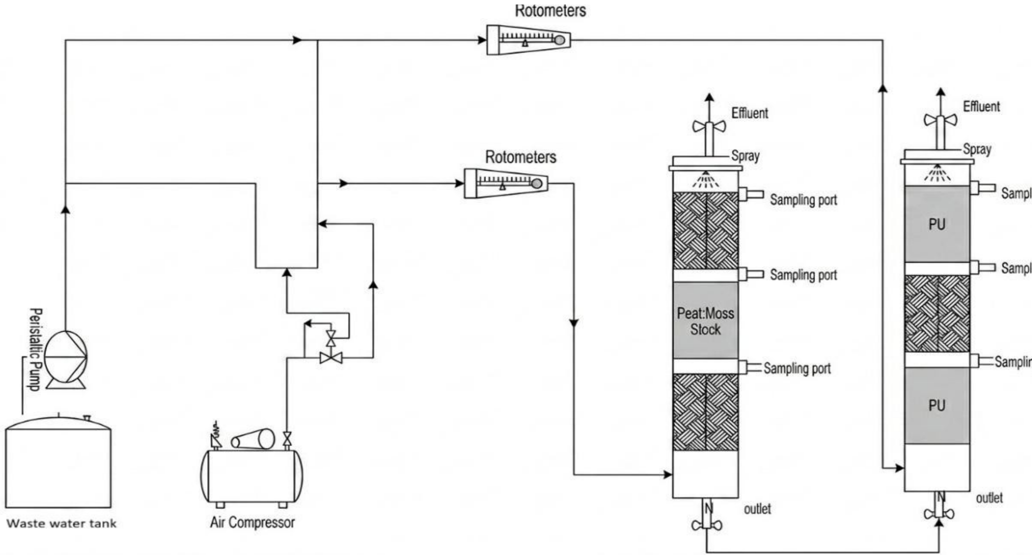

Figure 4: Schematic diagram of the biofiltration set up

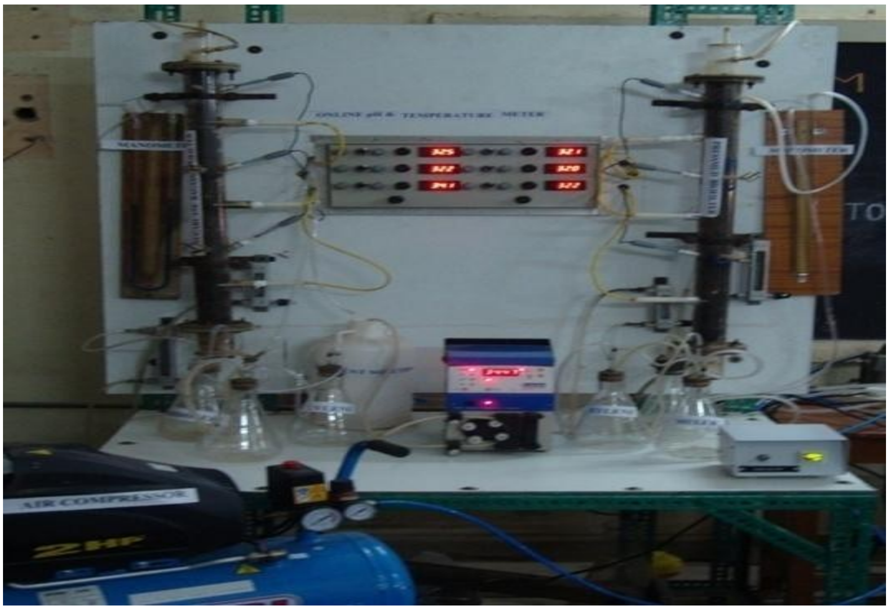

Figure 5:Real life image of biofiltration set up

A peristaltic pump (Miclins India limited, model PP 30 X) is used for the tannery waste water addition in to the reactor. The pump has an adjustable speed of 0 rpm to 3000 rpm and 8 mm silicon tubing is used for transferring the liquid. The nutrient is sprayed from the top of the bio-filter. Air compressor (Analab, India) is used to generate the air flow rate. U – tube water manometers are used for measuring pressure drop across the packed columns. Flow meters (Planck India limited, India) with a capacity up to 50 liter per minute are used to measure the flow rates

2.5 Measurement of VOC Concentration and Biofilter Performance Evaluation

The concentration of the VOC in the effluent before and after the biofiltration process is measured with the help of gas chromatography. Desired concentration of VOC in effluent is achieved by simple dilution with distilled water. The removal efficiency (%) of the biofiltration process was evaluated by comparing the inlet and outlet concentrations of VOCs. The removal efficiency, inlet loading rate, elimination capacity are calculated using the Equations (2), Equations (3) and Equations (4).

$$\text{Removal efficiency (RE in \%)} = \frac{\text{(Difference in Inlet and Outlet Concentration) x 100}}{\text{Inlet concentration}} \quad (2)$$

$$\text{Inlet Loading Rate (ILR)} = \frac{\text{Flow rate x Inlet concentration}}{\text{Volume of the reactor}} \quad (3)$$

$$\text{Elimination Capacity (EC)} = \frac{\text{Flow rate x (Difference in Inlet and Outlet Concentration)}}{\text{Volume of the reactor}} \quad (4)$$

The concentration of the VOCs in the inlet and outlet effluent was determined by analyzing the area under the peaks. Area is directly proportional to the concentration and different VOCs exhibit different response factor.

In the experimental setup, each biofilter column was packed with 75 cm of active bed material, comprising the selected packing medium (pearl millet or polyurethane foam) and inoculated activated sludge**.** Since biodegradation occurs exclusively within this packed section**,** the effective volume of the biofilter for VOC removal calculations was based solely on this 75 cm bed height**.** This ensured accurate computation of parameters such as ILR, EC, RE, which are directly influenced by the active biodegradation zone within the reactor.

3.0 Results And Discussion

After fabricating the biofiltration set up, a control experiment was carried out to measure the removal of VOC under the operational condition. In the control experiment, the reactor is packed with pearl millet stack without inoculation of microorganism. During the 5 days of control experiment, the decrease in VOC is observed in the range of 2.3 to 2.9%. This negligible decrease in the outlet concentration is attributed to the stripping or volatilization, The reactor is then packed with microorganism inoculated packing material and the experiments are carried out. The experiment was run continuously for 180 days and the parameters were changed as the process was on progress. Three important parameters that would affect the decomposition of the VOC in the reaction i.e time, flow rate and VOC concentration were taken into consideration for the comparison study. Concentration of the VOC taken in the range 0.2g/L to 1.0g/L and the flow rate was from $3x10^{-4}$ to $1.2x10^{-4}m^3/h$. The sample water after biofiltration is analysed by GC and the concentration was calculated based on the peak area.

The whole experiment carried out for 210 days has been represented in Figure 6. There are four phases in the graph and in each phase the inlet concentration of the VOC is increased from 0.2g/L to 1g/L. The elimination capacity slightly decreases while increasing the concentration and then increases gradually. As the inlet concentration increases outlet concentration increases

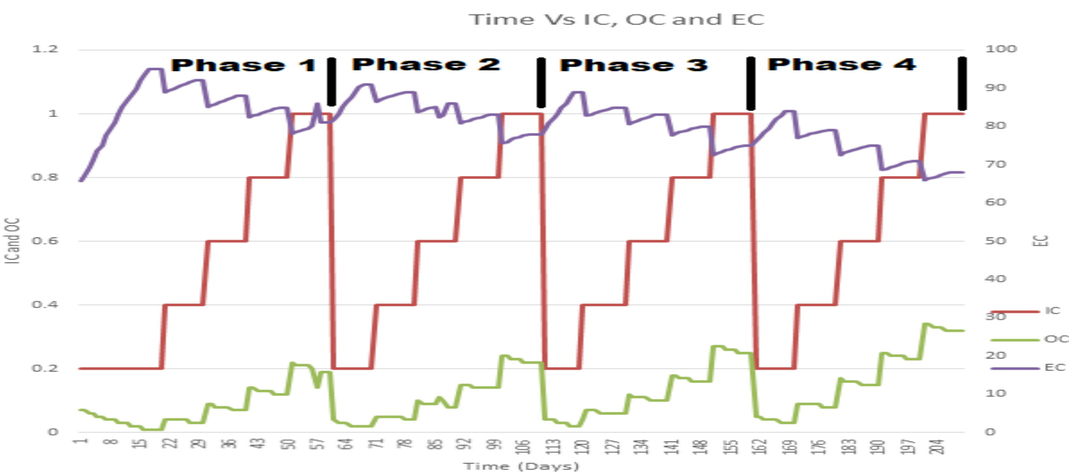

Figure 6: Flow rate of Phase 1 - 0.0003, Phase 2 - 0.0006, Phase 3 - 0.0009, Phase 4 - 0.0012 (m^3/h). In each Phase the inlet concentration of the VOC in the effluent is raised as 0.2, 0.4, 0.6, 0.8 and 1.0 g/L

As it is evident from the **Table 5**, the removal efficiency increases as the time increases and reaches the maximum after 15-16 days irrespective of the packing material. It is obvious that the microorganisms multiplied over the period and oxidatively decomposed the VOC.

Table 5: Effect of time period on the removal efficiency

Time period (Days)	Pearl Millet Stack	Poly urethane Foam	Mixed Pearl Millet Stack and Poly urethane Foam
1	65.80	60.00	62.9
2	67.20	62.00	64.6
3	69.40	63.00	66.2
4	71.50	68.00	69.8
5	73.60	69.00	71.3
6	75.10	70.00	72.6
7	77.60	73.00	75.3
8	79.10	75.00	77.1
9	81.10	77.00	79.1
10	83.30	80.00	81.7
11	85.10	81.00	83.1
12	86.90	82.00	84.5
13	88.10	85.00	86.6
14	89.90	86.00	88.0
15	91.80	88.00	89.9
16	93.20	91.00	92.1
17	95.00	91.80	93.4
18	95.00	91.80	93.4
19	95.00	91.80	93.4
20	95.00	91.80	93.4
Conditions: Flow rate 0.0003 m^3/h, concentration of VOC = 0.2 g/L			

The removal efficiency is observed maximum with pearl millet stack followed by mixture of pearl millet stack and polyurethane mixture and then polyurethane, **Figure 7**. Though, several explanations could be given for this observation, it is mainly attributed to the bioorganic nature of the pearl millet stacks, which may be better environment for the growth of microorganism. This is evident from the increased efficiency of the polyurethane + pearl millet packing material. The hydrophobic sites in the polyurethane are expected to have less affinity to microorganism. The change in the removal efficiency is in the range of 7 to 8% for every four days up to 16th day and it decreases sharply after that, **Figure 8**.

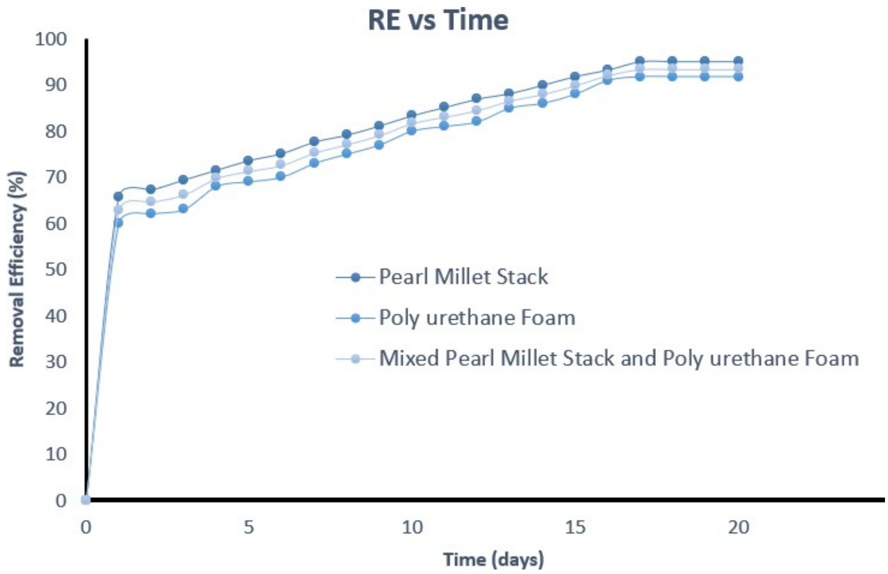

Figure 7: Removal efficiency Vs Time period

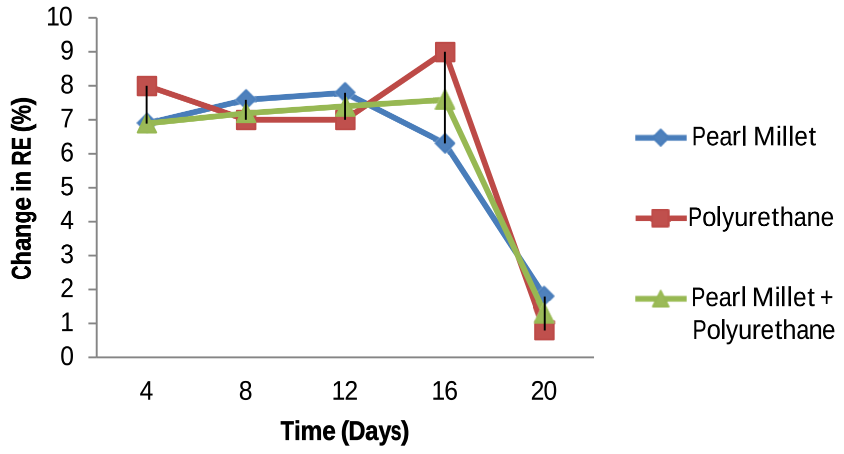

Figure 8: Time period Vs change in removal efficiency

In another phase of this study, the concentration of the VOCs was changed from 0.2g/L to 1.0g/L gradually by 0.2g/L for every 15days and the removal efficiency was calculated. The result obtained was consistent with the previous result: reached constant level after 15days. Also, the efficiency was found maximum for pearl millet stack packing material. The removal efficiency followed a different pattern with increase in concentration. The efficiency increased from concentration 0.2g/m^3 to 0.4g/m^{3}and decreased gradually when the concentration was further increased, **Figure 9**.

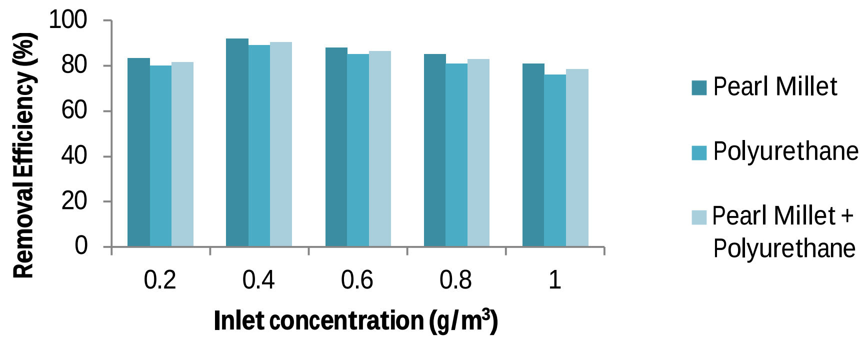

Figure 9: Effect of inlet concentration on RE

The influence of flow rate of effluent (0.3 x10^{-3} m^3/h to1.2 x10^{-3} m^3/h) on RE was observed at constant concentration of VOC (0.4g/L). Better efficiency is observed at lower flow rate and gradual decrease was observed at higher flow rate. This may be attributed to the decrease in the time period for the effluent inside the bio filter. It is interesting to note that though the out flow doubled when the flow rate is increased from 0.3 to 0.6 (x10^{-3} m^3/h), the decrease in the removal efficiency is minimal, **Figure 10**.

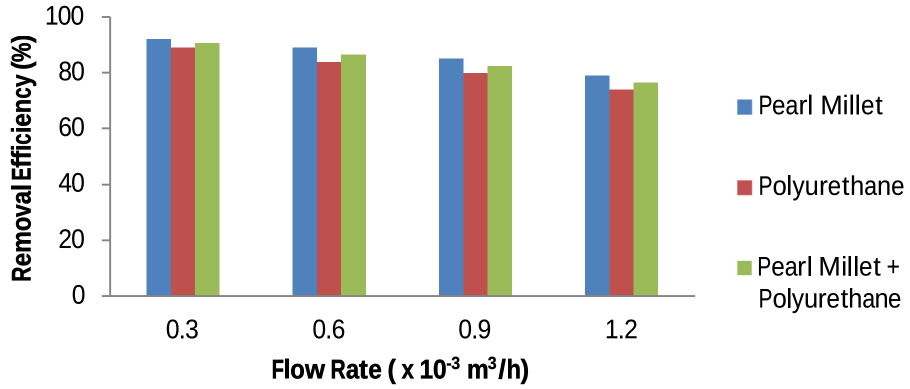

Figure 10: Effect of flow rate on RE

A representative graph between inlet loading rate (ILR) and the elimination capacity of the pearl millet stack is given in **Figure 11**. A similar pattern was observed with polyurethane as well as pearl millet stack and polyurethane mixture. A steady increase in the elimination capacity was noted with increase in the inlet loading rate which clearly indicates the efficiency of the reactor. Since the concentration of the VOC in the effluent is in the range of few ppm, ILR is limited to the maximum of 5.09. In the given range of ILR, the elimination capacity increases continuously without any considerable decrease which demonstrates the performance of the bioreactor even at high concentration

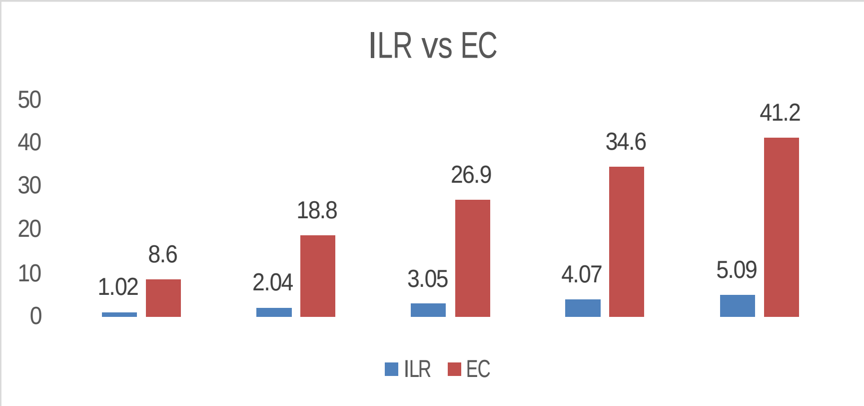

Figure 11. Inlet loading rate Vs Elimination capacity of pearl millet stack packed biofilter at constant flow rate of 3 x 10^{-4} m^3/h for pearl millet stack packing material

It is interesting to observe a steady increase in the elimination capacity irrespective of the inlet concentration, **Table 6**. Higher the concentration of the inlet loading higher is the elimination capacity. At a given concentration, when the flow rate is doubled the elimination capacity is also doubled. Similarly at a given flow rate doubling the concentration doubled the elimination capacity. Thus a linear correlation is observed between flow rate and elimination capacity,

Figure 12. A calibration curve can be drawn between flow rate and elimination capacity and the approximate elimination capacity may be predicted.

Table 6: Effect of flow rate and concentration on elimination capacity

FR 10^{-4} m^3/h	EC at Constant Concentration g/L				
	0.2	0.4	0.6	0.8	1
3	8.6	18.8	26.9	34.6	41.2
6	18.3	36.6	52.9	67.2	79.4
9	27.5	51.9	76.4	97.7	114
12	34.6	65.1	91.6	116	138.4

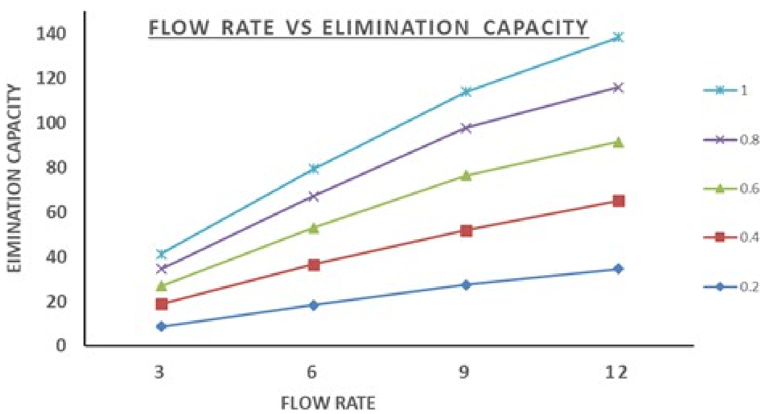

Figure 12: Flow rate Vs Elimination capacity at various concentration

After completing the experiment, the changes in the pearl millet stack packing material was investigated. The material was removed from the reactor, thoroughly washed with water to eliminate microbes and contaminants, and air-dried at room temperature for two days. It was then analyzed using Infrared (IR) spectroscopy with a KBr pellet, **Figure 13**. The used packing material appeared black, suggesting significant alteration compared to the unused material. Surprisingly, the IR spectra of the used and unused pearl millet stack showed minimal differences in the 1200–3500 cm^{-1} region. However, a reduced peak intensity at 1100 cm^{-1} in the used material indicates cleavage of the weak carbohydrate C-O bond in cellulose.

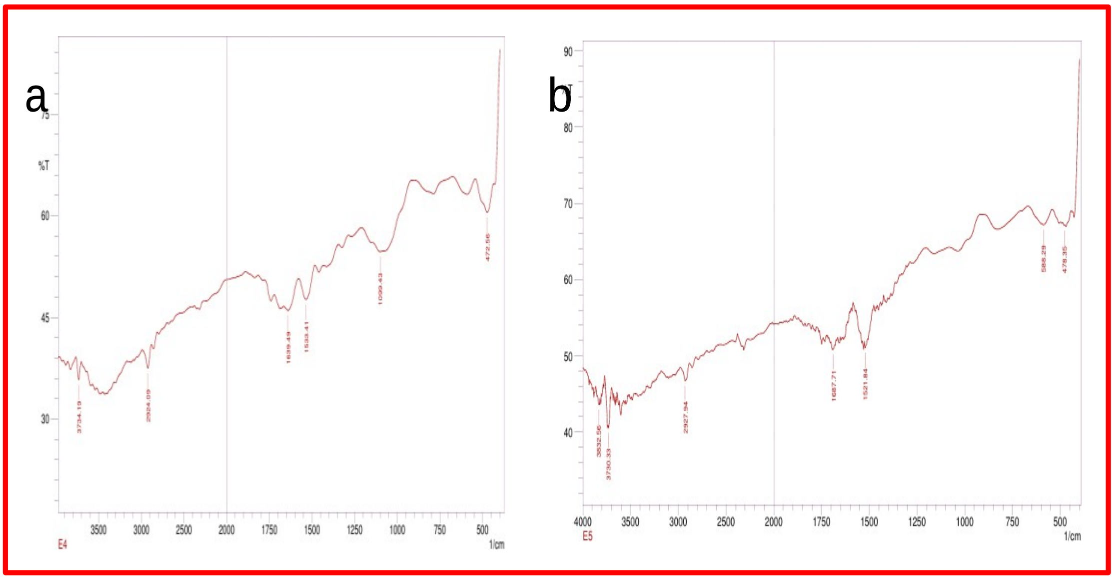

Figure 13: IR spectrum of the Pearl millet stack (a) before and (b) after biofiltration

The results demonstrate that the biofiltration system was effective for VOC removal, with the performance strongly influenced by packing material, acclimatization time, inlet concentration, and flow rate. The control run showed only 2.3–2.9% VOC reduction, confirming that natural stripping or volatilization contributed negligibly and that the observed removal in the inoculated reactor was mainly biological (Nayyeri et al., 2022). Once microorganisms were established, removal efficiency increased steadily and reached a stable maximum after about 15–16 days, which clearly reflects microbial growth and adaptation on the packing media. Among the three media, pearl millet stack consistently performed best, followed by the mixed bed and polyurethane foam (Shin et al., 2026; Chatzis et al., 2026). This suggests that the bioorganic surface of pearl millet provided a more favorable habitat for microbial attachment and oxidation, while the hydrophobic polyurethane surface supported less microbial colonization.

The influence of operating parameters was also clear. As inlet VOC concentration increased, removal efficiency initially improved from 0.2 to 0.4 g/L, but declined at higher concentrations, indicating possible saturation of microbial activity or mass transfer limitations. Similarly, higher flow rates reduced removal efficiency because the residence time in the reactor became shorter (Ali et al., 2026). The elimination capacity increased with inlet loading rate and showed a nearly linear relationship with both concentration and flow rate, demonstrating that the reactor could handle higher pollutant loads effectively (Mondal et al., 2026). The IR analysis of used pearl millet stack further confirmed interaction with the VOC-degrading environment, as the reduced peak intensity near 1100 cm^{-1} suggests partial cleavage of cellulose C–O bonds. The results confirm that pearl millet stack is a promising, low-cost biofilter packing material for tannery VOC treatment.

4.0 Conclusion

The study shows that biofiltration is a technological solution that can effectively remove VOC from tannery effluents and is environmentally friendly. Pearl millet stacks had the highest removal efficiencies of up to 95 % among the tested packing materials and thus proved to be a suitable packing material for the low cost and sustainability in biofilter media. The better performance seen after 15-16 days of operation is an indication of microbial acclimatization; microbial biofilm must be established and acclimatized before it can attain its maximum degradation capacity. Agricultural waste-based materials are also found to be effective as VOC treatment materials in comparison to conventional synthetic materials such as pearl millet stacks and polyurethane foam. Pearl millet stacks are especially appealing for industries looking for practical and environmentally friendly emission control solutions. The system proved to be effective, but the relatively long time for 90% VOC degradation suggests that further optimization of the system is required for larger scale application.

Future works should concentrate on increasing the degradation rate and shorten the start-up period of the biofilter. An important area to be optimized is the bed height, as the longer the bed, the more time a polluted air stream will spend in contact with the active microbial biomass, which will lead to better mass transfer and pollutant removal. An additional beneficial approach is to load the microbial inoculum to get the biofilter operating at a more efficient operational state in a shorter period of time and more quickly stabilize the degradation performance. Furthermore, systematic studies of the effects of inlet VOC concentration, flow rate, moisture content, pH, and nutrient supplementation are needed to determine the best operating window for long-term treatment. In order to assess its applicability for real tannery operations, pilot- and field-scale testing would require scaling up of the reactor. The studies should include pressure drop, packing compaction, bed clogging and stability of microbial community for long term under fluctuating industrial loading. It would also be beneficial to do a comparison test of pearl millet stack with other readily available agricultural residues in the region to know if similar or even better outcomes could be obtained with other low cost materials. Future research should focus on the treatment of mixed VOC mixtures, not just on the treatment of individual VOCs, because tannery emissions typically have multiple pollutants. The combination of this biofiltration with other pollution control technologies can offer a more powerful and scalable solution for sustainable management of tannery effluents.

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Author Contributions

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