Removal of toluene from air- scream using semi industrial two-phase bioscrubber with cutting oil: An intervention study

Mohammad Nourmohammadi (nourmohammadim@mums.ac.ir)
Mashhad University of Medical Sciences
Farideh Golbabaei Golbabaei
Tehran University of Medical Sciences
Ali Karimi
Tehran University of Medical Sciences
Ebrahim Taban
Mashhad University of Medical Sciences

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Abstract

Toluene is a single-ring aromatic, which is widely used in various industrial processes. Regarding to harmful effects to human, the aim of this study was removal of toluene from the airflow using industrial-scale low-pressure two-phase bioscrubber with cutting oil. The design of the bioscrubber of the present study consisted of two parts of the adsorption column and a. Also, cutting oil was added at concentrations of 5%, 7.5% and 10% as organic phases and tested. The results show that after 72 hours with increasing organic phase concentration, toluene concentration was further decomposed compared to the control sample. The results showed that the use of 5% concentration of cutting oil increased the efficiency from 22% in the case of no organic phase to 55% in the case of using 5% of cutting oil. At a concentration of 7.5%, the lowest efficiency was 38% and the highest was 63%. Also, the minimum and maximum removal capacity are 17 and 269 $g/m^3.h$, respectively. Efficiency at a concentration level of 5% of cutting oil as an organic phase is better than a concentration of 7.5%. In this study, for the first time in Iran, cutting oil was used as an organic phase, which showed that cutting oil in concentrations less than 10% had no effect on the growth of microorganisms. The results showed that shear oil and silicone oil increased the adsorption of volatile organic compounds in bioscrubber.

1. Introduction

Volatile organic compounds (VOCs) are one of the most important sources of air pollution that have effects on the human health and environment(1, 2). Environmental aspects of these contaminants, such as stratospheric ozone depletion, which protects the terrestrial organisms from ultraviolet radiation, are the production of ozone around the earth and global warming(3, 4). Toluene is a single-ring aromatic VOC, which is widely used in various industrial processes. This compound is produced in large quantities by consuming fossil fuels. It is also used in industries as a solvent in the preparation of paints, adhesives, rubbers, plastics, and the production of various chemical compounds. Although toluene is less toxic than benzene and is not considered a carcinogen, its combination with other substances increases its carcinogenic effect(5, 6).

The high harm of toluene to humans and the environment shows the importance of removing this substance from the air stream. Two groups of methods including common methods (physical-chemical) and biological methods have been used to remove VOCs from the air stream(7). Disadvantages of common methods for removing these compounds from the air stream include the high cost, use of chemicals that are mostly expensive, and the production of waste materials (chemical solvents and activated carbon). Also, the disposal of these materials requires safe operating methods(8). On the other hand, biological methods or biodegradation are more economically and environmentally sound (no production of secondary contamination). Airflow treatment methods, based on the ability of some microorganisms (mainly bacteria), to decompose a wide range of organic and inorganic compounds due to low environmental impact and low operating costs compared to physico-chemical methods are a good choice for environmental controls(9).

The first recorded uses of biological decomposition date back to about 60 years ago, in the 1950s, when this method was used to control the odors, especially those from wastewater treatment and disposal units(10). Carlson et al. first introduced soil-based biofilters in 1966 as an advanced odor control process. After the expansion of the use of biodegradation, several equipment was built based on it. Biofilters and bioreactors can be mentioned among the air purification equipment based on microorganisms(11). One of the most important bioreactors of air purification is bioscrubber which consists of two parts, the absorption part and the bioreactor. In the adsorption unit, gaseous contaminations are transferred to the liquid phase. In this part, the gas and liquid phases pass through the absorption column in a reverse flow. The liquid phase containing the target contaminant is then transferred to the bioreactor. The bioreactor unit contains a suspension of suitable microbial species and nutrients for the growth of microorganisms(12).

For removing the VOCs using a bioscrubber, the liquid phase is usually water. However, new studies have shown that the organic phase is also effective in increasing the removal efficiency. Fouhy showed that two-phase bioscrubber with water/silicone oil increases the adsorption of hydrophobic molecules by 10 to 30%(13). Darracq et al. also stated that silicon oil with a concentration of 20 to 30% optimally removes hydrophobic compounds such as toluene. Therefore, studies have shown that bioscrubbers with operating costs of 1.2 to 1.4 operating costs of chemical scrubbers and better efficiency than drip filters are a suitable alternative to biofiltration(14). The results of the study by Oliver et al. showed that the removal capacity of toluene, which is more biodegradable than monochlorobenzene, was higher in the bioscrubber than the drip filter(15). Muldiar et al. also showed that bioscrubners were more efficient than the other methods for removing organic compounds at higher concentrations. In addition, the type of organic phase used in bioscrubber is also very important. As mentioned in previous studies, silicone oil has usually been used for the organic phase(16).

Regarding the reduction of emission and removal of toluene compound, the biological removal of this substance is mainly done with the silicone oil as the organic phase. Based on the knowledge of the authors of the present study, so far, few studies have been performed on the efficiency of two-phase bioscrubbers on an industrial scale using the cutting oil as organic phase to remove toluene. Therefore, the aim of this study was removal of toluene from the airflow using industrial-scale low-pressure two-phase bioscrubber with cutting oil.

2. Methods

The present interventional study was designed and performed with the aim of removing toluene from the air stream using an industrial scale low-pressure two-phase scrubber. In the present study, low pressure industrial scale bioscubbers were designed and manufactured. The design of the bioscrubber of the present study consisted of two parts of the adsorption column for the separation of contamination from the gaseous phase to the aqueous phase and a bioreactor for the biodegradation of toluene by decomposing microorganisms and its conversion to carbon dioxide and water. Also, in order to increase the efficiency of the organic phase scrubber, cutting oil was added at concentrations of 5%, 7.5% and 10% as organic phases and tested.

2.1. Absorption column :

In order to build an industrial-scale absorption column according to the scrubber design standards, a stainless-steel scrubber with a height of 1.2 meters and a diameter of 30 cm was selected (Height to diameter ratio = 4). The body of the scrubber was made of two parts connected by installing a flange at the end of each part. In the first part with a height of 60 cm and a diameter of 30 cm, the air outlet was installed. The second part is the air inlet and the liquid phase inlet along with the scrubber cone, which has a diameter of 30 cm at the beginning of the cone and a diameter of 3 cm at the end. Also, the size of the scrubber inlet was 4 cm (Fig. 1).

The proper detention time in the scrubber is between 5 to 15 seconds; therefore, in the present study the detention time was considered 10 seconds. Also, another important parameter in the design of the bioscrubber is the volumetric velocity of the air, which was calculated with a detention time of 10 seconds at a speed of 4 cfm. The hydrophobicity of toluene causes the use of water alone in the liquid phase to lead to very low adsorption efficiency, so in this study in order to increase the solubility of toluene and its greater absorption in the liquid phase, we used the cutting oil as the organic phase. As a result, the liquid phase of the bioscrubber consisted of three parts: water, organic phase, and nutrients needed for the growth of microorganisms. In selecting the organic phase, it should be considered that the organic phase is a suitable solvent for hydrophobic compounds and has a good diffusion coefficient in water to perform the adsorption process optimally. The cutting oil used in this study was Viyer 5000 with characteristics such as the density of 0.86, pH of 9.5, and white appearance.

Given that cutting oil manufacturers introduce one of the features of their product as having bactericidal substances, one of the objectives of this study was to determine the concentration of cutting oil that has no effect on microorganisms. For this purpose, sludge containing toluene decomposing microorganisms was inoculated in concentrations of 10%, 20%. and 30% of cutting oil along with broth nutrient, and after 24 hours it was cultured on agar nutrient. The results showed that cutting oil at concentrations below 10% had no effect on the growth of microorganisms. Therefore, the study was performed on concentrations of 5, 7.5 and 10%.

Due to the high toxicity of toluene vapors, all equipment and devices used in this study were placed under a laboratory hood that was designed and manufactured with a length and width of 220 and 90 cm, respectively, and 440 ft^3/min flow rate. To create a normal flow in the cross section of the hood, two slots were installed at the end of the hood, along the length. In order to prevent the heating and cooling equipment from cooling down due to the air flow in the hood, all the paths in which the air flow was present were covered with thermal insulation.

2.2. Bioreactor design:

The bioreactor consisted of three parts: tank, pump and stirrer. The tank consisted of two settlements and a feeder, where the liquid was transferred from the feeder by a pump to the adsorption column. The body of the bioreactor tank was made of 6 mm thick glass in the shape of a rectangular cube. Also, the required air was supplied by the model fan (Air Flow) with variable speed. The supplied air was absorbed into the column by the transmission system and the flow rate was measured and adjusted by TES-1340 thermal anemometer and Pito tube. In order to recirculate the liquid phase of the bioreactor, the Italian water pump Pumptax model CM100/01 with a flow rate of 20 to 90 liters per minute, 1 horsepower, 220 volts and a head of 25 to 33 meters was used (Fig. 2).

2.3. Microbial Consortium:

In this study, the treatment plant of Tehran refinery was the source of toluene degrading microorganisms. For this purpose, sampling was performed from the treatment part of the sludge in the Tehran refinery. Bottle culture method was used for culturing toluene degrading microbial strains. In this method, the culture medium contained all the nutrients required by microorganisms, except the carbon source. Toluene is added to the culture medium as a carbon source. The nutrient salt solution used contained the main micronutrients, all of which are products of the company MERCK (German). To investigate and ensure the degradability of microbial strains in the sampled sludge and enrich the microbial population, 100 ml of a mixture of sludge and nutrient sample in a ratio of 3 to 1 was poured into three 500 ml bottles. 1 bottle was prepared as a control as in the original sample. However, KCN with a concentration of 1% by weight was used to kill the microorganisms. Then, 10 µl of toluene was injected into the bottles and incubated on a shaker at 90 rpm in a dark environment at 28°C. This experiment was performed once by adding a certain concentration of cutting oil to the nutrient liquid mixture and sludge sample. After 72 hours, the samples were taken from the top of the sample and control bottles using a gasified Hamilton syringe, and the samples were injected into the GC device to determine the concentration of toluene. After determining the ability of microorganisms to decompose toluene, they were propagated for use in bioreactors.

For measurement of toluene phase concentration, The GC equipped with Flame Ionization Detector (GC-FID) (model Varian CP-3800, Varian Technologies Japan) was programmed at 130°C for column, split ratio of 5 and injector and detector temperature of 240°C and carrier gas flow rate was 1.8 ml/min. To determine the different concentrations of toluene in the samples, first certain concentrations of toluene were made in Tadlar bags. 100 µl of the air sample was injected to GC to sketch the calibration curve, samples were collected from the two sampling ports that placed in the inlet and outlet of absorption column and then directly injected into GC by gas tight syringe (Hamilton US). The resulting area were also compared with a calibration curve of gaseous toluene to determine the concentration of toluene in the samples

2.4. operational parameters:

Important operating parameters include inlet concentration (Mg/m3) and outlet concentration (Mg/m3), carbon dioxide concentration before and after the adsorption column, biomass content (g/l), residence time, removal efficiency (%), and elimination capacity (g/m3.h). The concentration of toluene at the inlet and outlet of the bioscrubber was obtained by sampling with a Hamilton syringe and injecting by gas chromatography.

Removal efficiency (RE)

Determination of removal efficiency by inlet and outlet concentration was calculated by the following formula.

Equation 1

$$RE(\%) = \frac{\text{Cin} - \text{Cout}}{\text{Cin}} \times 100$$

RE: Removal efficiency (%) C_{in}: Inlet contaminant concentration mg/m3

C_{out}: Outlet contaminant concentration mg/m^3 Elimination Capacity (EC) (g/m^3.h)

The elimination capacity was calculated according to the following formula, which indicates the consumption capacity of the contaminant entering the bioreactor per unit volume of the bioreactor in a specified period of time.

Equation 2

$$EC = \frac{\text{Q}(\text{Cin} - C_{out})}{\text{V}}$$

Where, EC is elimination capacity (g/m^3.h), Q is the inlet gas flow rate, C_{in} is the contaminant concentration at the bioscrubber inlet, C_{out} is the contaminant concentration at the bioscrubber outlet (mg/m^3), and V is the bioscrubber volume (m^3).

Equation 3

$$L = \frac{C \times Q}{V}$$

Contaminant load (L): (g/m^3.h)

The concentration of toluene at the inlet and outlet of the bioscrubber was obtained by sampling with a Hamilton syringe and injecting by gas chromatography. The concentration of carbon dioxide was determined using a direct reading device Testo model 535-CO2 equipped with an infrared sensor. The amount of biomass was also measured using a 50 cc Falcon gravimetric method and a centrifuge at 4000 rpm.

3. Results

3.1. Degradability of microorganisms for toluene

The results of investigating the degradability of microbial strains in the sampled sludge with or without organic phase in different concentrations of 10%, 20%, and 30% (samples 1, 2 and 3) show that after 72 hours with increasing organic phase concentration, toluene concentration was further decomposed compared to the control sample (Fig. 3). As shown in the Figure, in the control sample whose bacterial population was killed by KCN, the concentration of toluene in the control sample was 1300 ppm, and in the main samples it was 34, 40 and 44 ppm, respectively. Also, dissolved oxygen in the control sample was 9.8 mg/l and in the main samples it was 2.1 mg/l, which indicates the consumption of oxygen by microorganisms.

3.2. Mass transfer rate

Figures 4 and 5 show the concentration of toluene at the saturation point in different concentrations of cutting oil and in one- and two-liter flow rate. The results showed that the concentration of toluene for water reached saturation with the shortest time. For a concentration of 10% cutting oil, the results showed that 50% of toluene was absorbed after about 200 minutes and then the concentration in the gas phase increased until the inlet and outlet concentrations were equal. It also halved the time by doubling the flow rate. The results showed that the use of cutting oil increases the concentration of toluene in the liquid phase and also increases the saturation time. Due to the fact that at concentrations greater than 10%, there was no significant difference in concentration in the liquid phase and the mass transfer coefficient, and the growth of microorganisms at concentrations higher than 10% is very low. In this study, a concentration of less than 10% was used for the performance of the bioscrubber.

3.3. Operational parameters:

The results of bioscrubber performance at concentrations of 5%, 7.5% and 10% of cutting oil are shown in Table 1. The results showed that the use of 5% concentration of cutting oil increased the efficiency from 22% in the case of no organic phase to 55% in the case of using 5% of cutting oil.

Table 1
Bioscrubber performance in removing toluene at different concentrations of cutting oil (5%, 7.5% and 10%)

Operational parameters	**Different concentrations of organic phase**								
	5%			**7.5%**			**10%**		
	Minimum	**Maximum**	**Mean (SD)**	**Minimum**	**Maximum**	**Mean (SD)**	**Minimum**	**Maximum**	**Mean (SD)**
Inlet concentration Mg/m^3	178	1507	729 (400)	130	1350	646 (407)	331	776	562 (190)
Outlet concentration Mg/m^3	62	930	4440 (238)	47	820	235 (105)	138	540	253 (96)
Contaminant load g/m^3.h	63	533	330 (180)	6.2	103	45 (32)	117	247	210 (85)
Removal efficiency (%)	35	65	55 (8.8)	38	63	53 (9.5)	30	58	45.8 (7.3)
Elimination capacity g/m^3.h	30	227	110 (62)	17	291	129 (91)	38.9	163	99 (40)
Percentage of carbon mineralization	18	42	33 (6)	12	53	38 (15)	21	34	28 (5.8)
The amount of biomass g/l	0.8	23	13 (4)	1	19	15 (5.4)	1.5	32	19 (8)

Figure 6 also shows the trend of changes in the functional parameters of the bioscrubber at different concentrations of the cutting oil. As the figure shows, the removal efficiency in all three concentrations is upward over time, but at a concentration of 10% the slope of the chart is higher. Also, at a concentration of 5%, the removal efficiency and toluene removal capacity at input concentrations of 178 to 1507 mg/m^3 show that the minimum efficiency was 35% and the maximum was 65%. Also, the minimum and maximum removal capacity are 30 and 227 g/m^3.h, respectively. At concentrations above 1507 mg/m^3, no increase in efficiency was observed and this could be due to poisoning of microorganisms. As shown, the addition of cutting oil as an organic phase increases the removal efficiency and removal capacity of toluene. At a concentration of 7.5%, the lowest efficiency was 38% and the highest was 63%. Also, the minimum and maximum removal capacity are 17 and 269 g/m^3.h, respectively. Efficiency at a concentration level of 5% of cutting oil as an organic phase is better than a concentration of 7.5%. However, the removal capacity is higher at a concentration of 7.5% compared to 5% and this is due to a change in the input concentration of toluene.

The results showed that the removal efficiency of bioscrubber increased with increasing the organic phase concentration from zero to 10%, but increasing the concentration from 0 to 5% is severe and gradually increases the organic phase percentage to 7.5% and decreases with increasing concentration to 10% removal efficiency (Fig. 7). This result is slightly different in terms of removal capacity.

4. Discussion

The aim of the present study was to remove toluene from the gas phase using an industrial-scale low-pressure two-phase scrubber. The bioscrubber used in this study consisted of two scrubber sections to separate toluene from the gas phase and transfer it to the aqueous phase, and a microorganism section that removed toluene from the scrubber effluent. Also, to increase the efficiency of the bioscrubber, two aqueous and organic were used in this study. The results of the study showed that the designed microorganism in the presence of organic phase with a concentration of less than 10% had the highest efficiency and also the efficiency and removal capacity of bioscrubber in the presence of organic phase with a concentration of 10% were higher than other organic phases.

To isolate the microorganisms that degrade VOCs, we should use them in environments where these microorganisms are naturally present. In various studies, to enrich the microbial population in order to decompose volatile organic compounds, they have used the soils around the tanks of oil refineries and gas stations(17), sewage or sludge of municipal and industrial wastewater treatment plants(18). In this study, the source of microorganisms was the return part of the refineries of Tehran refinery. The results of the present study showed that the concentration of toluene in the control sample whose bacterial population was killed by KCN was 60 times higher than the samples containing the bacterial consortium. It can be concluded that toluene is degraded by the microorganisms in the bottle. Color change in the original samples indicated the growth of microorganisms in the sample bottles.

Due to the fact that toluene is a hydrophobic compound, in order to increase the absorption in the liquid phase, various compounds are used, which must have properties, one of which is the lack of effect on microorganisms. One of the compounds used in this study is cutting oil, which is widely used in industry and is cheap and available. As the results showed, adding cutting oil in concentrations less than 10% has no effect on reducing the growth of microorganisms. However, at concentrations of 20 and 30%, the growth of microorganisms is significantly reduced compared to the control sample, which can be due to the use of side bacteria in the composition of this oil, which at concentrations of 20 and 30% causes an effect on microorganisms. Lalanne et al. also showed that cutting oil had no effect on the population of microorganisms(19). A study by Fabian et al. to investigate the growth of bacteria in oil-soluble emulsions found that the use of cutting oil had no effect on the growth of microbial populations in the emulsion. They also showed that with increasing the concentration of organic phase, the microbial population in the logarithmic phase decreases(20). In a study by Bennett et al., 30 different species of bacteria survived at 9 concentrations of cutting oil. Gram-negative bacteria were able to survive for a considerable time, while gram-positive bacteria died very quickly. Darracq et al. also examined the biodegradation of silicone oil and concluded that silicon oil was not degraded by microorganisms and did not observe toxicity on the microorganisms(14).

In recent years, the use of two-phase systems to eliminate VOCs has been developed. In gas-liquid-liquid processes, mass transfer rate is a key parameter for estimating the bioreactor performance(21–23). The mass transfer coefficient depends on the physic-chemical properties of the pollutant and the characteristics of the adsorption medium (viscosity and salt content) as well as the internal properties of the reactor and operating conditions (gas viscosity, liquid viscosity, pH, and temperature). An important aspect of liquid-liquid systems was studied by Nielsen et al(24). They concluded that the use of organic phase increased the oxygen transfer. They found that this increase in oxygen transfer was due to the organic phase having solubility. They also found that the oxygen transfer coefficient in the bio-scrubber containing the organic phase was much lower than that of the aqueous phase bio-scrubber, which was consistent with the results of this study(18). As the results of the present study showed, by adding cutting oil to the liquid phase, the concentration of toluene in the gas phase was significantly reduced. This indicates that the contaminant is trapped in the liquid phase. Also, based on the results, adding cutting oil reduced the mass transfer coefficient (KLa) and increased the concentration of toluene in the liquid phase. Aldrich's study showed that the maximum oxygen uptake in silicon oil occurred with lower viscosity (Cst 10), and the mass transfer coefficient was directly related to the volume fraction of silicon oil. Cesario et al. observed an increase in toluene mass transfer in a 1: 1 ratio with the organic phase and an increase in oxygen mass transfer in a volume ratio of 10% of FC40 as the solvent. (25)Montes et al. also showed a tendency to absorb silicon oil for oxygen 10 times more than water(26). Karimi et al.'s study showed that the use of 10% by the volume of silicone oil significantly reduced energy consumption compared to concentrations of 20% and 30% in two-phase bioreactors. They also found that the optimum organic phase concentration of silicon oil in terms of oxygen transfer was 10%. They also observed that the use of silicone oil at a concentration of 10% reduced the oxygen transfer coefficient. Jean et al. reported that silicon oil at a concentration of 10% had no effect on the mass transfer coefficient(26).

Various studies have been performed to determine the effect of aeration on oxygen transfer rate(27). In this study, two pumps with constant flow were used in the bioreactor section to increase the amount of dissolved oxygen in the liquid phase. The results showed that the performance of bioscrubber in toluene purification without the presence of organic phase with increasing input concentration did not change the efficiency and removal capacity of toluene. The removal efficiency without organic phase was 20%, which is higher than the study of Lalanne et al., who reported the removal efficiency of toluene without the presence of organic phase at 11%, and this could be because the L/G ratio in this study was 3.6(28). It was much greater than the study of Lalanne et al. Malhautier et al. also used an industrial-scale scrubber to remove a mixture of VOCs including chlorinated, aromatic, and oxygenated compounds. In water, the removal efficiency was between 80% and 85% and for hydrophobic compounds such as toluene, the removal efficiency was reported to be 35%. Compared to the results of this study, toluene was on average 17% lower(19).

Due to the fact that the use of organic phase improves the performance of two-phase bioscrubber. Few studies have used cutting oil as an organic phase. One of the most important characteristics of cutting oil that can be used on an industrial scale is its low cost and availability. In the first part of this study, the results showed that cutting oil in concentrations above 10% could reduce the microbial population, which can reduce biodegradation in two-phase systems. The results of bioscrubber performance without the presence of organic phase showed that the efficiency and removal capacity of toluene were very low, which could be due to the hydrophobicity of the toluene compound. Cutting oil was used to increase toluene absorption in the bioreactor. Cutting increases the removal efficiency from 22% without the use of organic phase to 55% in the presence of 5% cutting oil. While Lalanne et al. obtained the removal efficiency of aromatic compounds in the bioscrubber, the results showed that the removal efficiency when using cutting oil increased from 12–36%(28). The removal efficiency in the absence of organic phase and using the organic phase was lower than that of this study, which may be due to the fact that the L/G ratio in this study was higher than the study of Lalanne et al. on of chlorinated compounds on microorganisms. In the study of Kan et al.'s examination of bio-removal of toluene and trichloroethylene in bioreactor emulsion, the results showed that the optimal concentration of oocyte alcohol as a phase was 3–5% and the increase of the organic phase was more. This amount has no effect on increasing the efficiency and removal capacity(29).

5. Conclusion

Based on studies, bioremediation methods such as biofilters, drip filters, membrane bioreactors and bioscrubbers can be used as potential methods to remove VOCs compared to conventional methods. However, the use of biological systems to remove these compounds is associated with challenges. In biofilters, increasing the flow rate and concentration of contamination can reduce the microbial population, and in drip filters, microbial growth can block and increase the pressure drop. However, in bioscrubber, these two limitations can be overcome and better control over its performance parameters can be reached. According to the results of this study, bioscrubber can be a good suggestion for the removal of volatile organic compounds in industry. In this study, for the first time in Iran, cutting oil was used as an organic phase, which showed that cutting oil in concentrations less than 10% had no effect on the growth of microorganisms. Industrial-scale scrubber was used to remove toluene from the air stream using organic phase and without using organic phase. The results showed that shear oil and silicone oil increased the adsorption of volatile organic compounds in bioscrubber. The liquid phase as well as the mass transfer coefficient can increase the bioremediation of these compounds. The results of the study on the function of this compound in bioscrubber showed that its use in bioscrubber significantly increased the efficiency and removal capacity of toluene from the air stream. Although various parameters such as temperature and amount of oxygen, pH and nutrients were considered in this study, further research on the effect of microbial parameters should be conducted to determine the optimal state.

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Figures

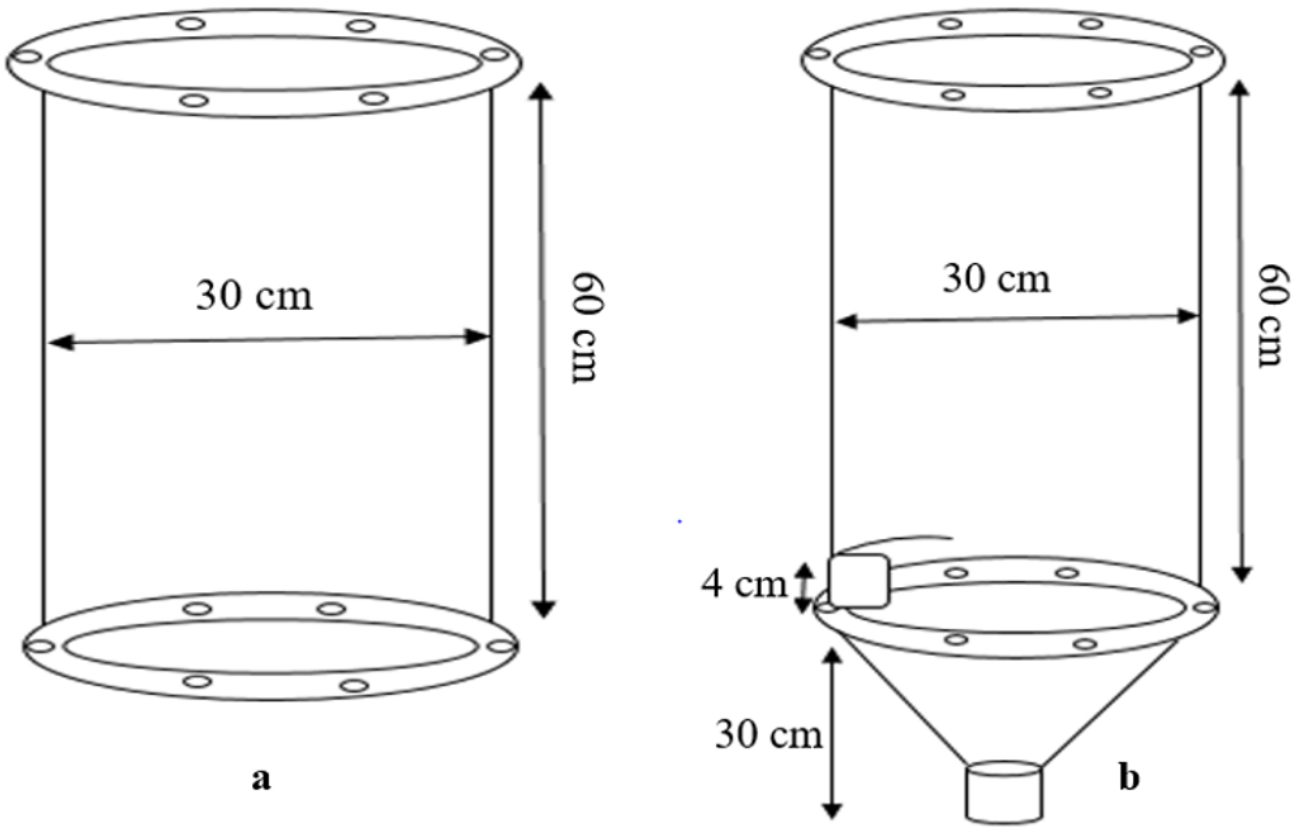

Figure 1

The absorption column in the designed bioscrubber

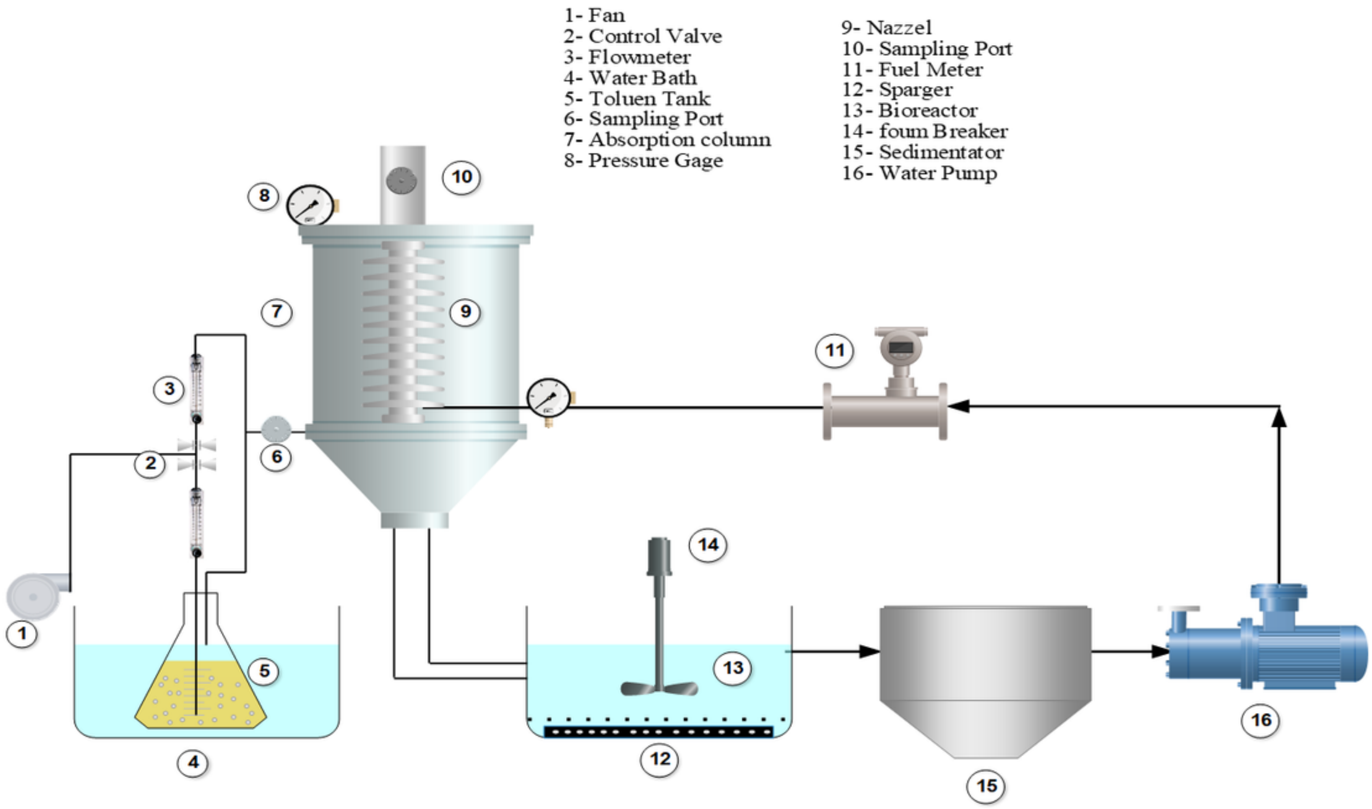

Figure 2

The schematic diagram of the bioscrubber

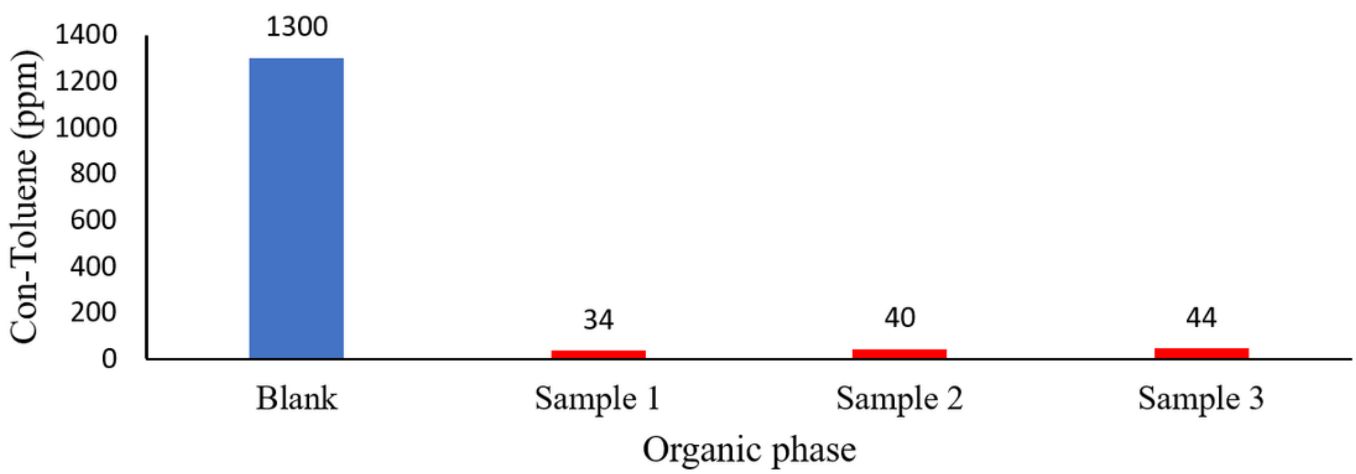

Figure 3

Toluene concentration and samples containing microorganisms in the absence of organic phase and organic phase with concentrations of 10%, 20% and 30%

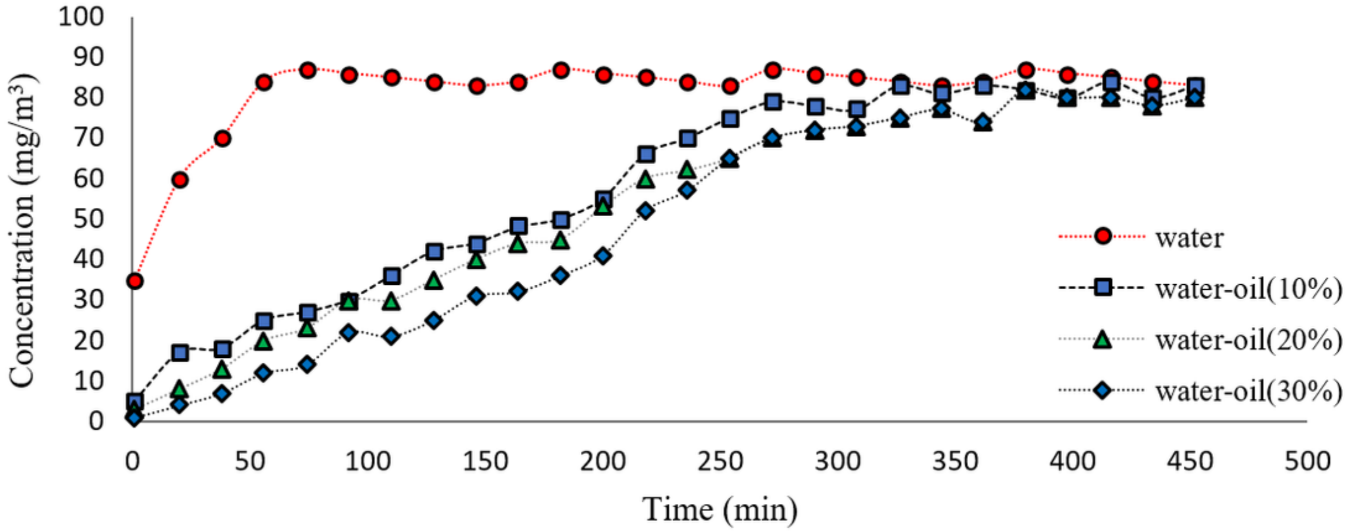

Figure 4

Concentration of toluene in the gaseous phase of the reactor outlet and different concentrations of cutting oil (flow rate 1 liter per minute)

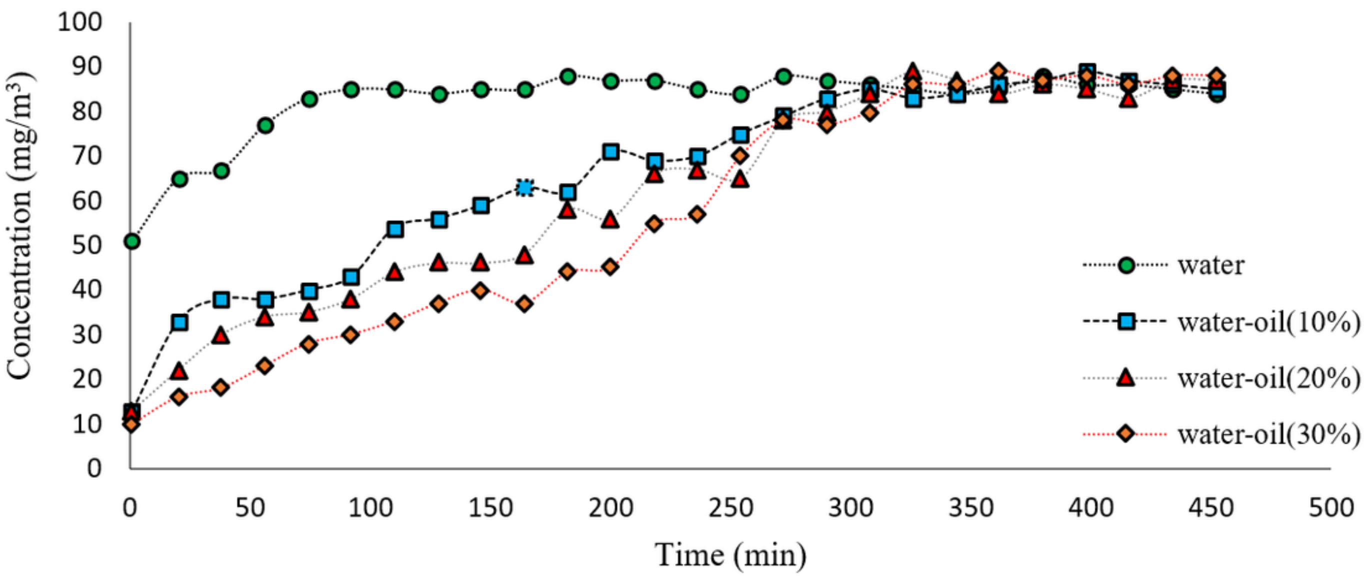

Figure 5

Concentration of toluene in the gaseous phase of the reactor outlet and different concentrations of cutting oil (flow rate 2 liters per minute)

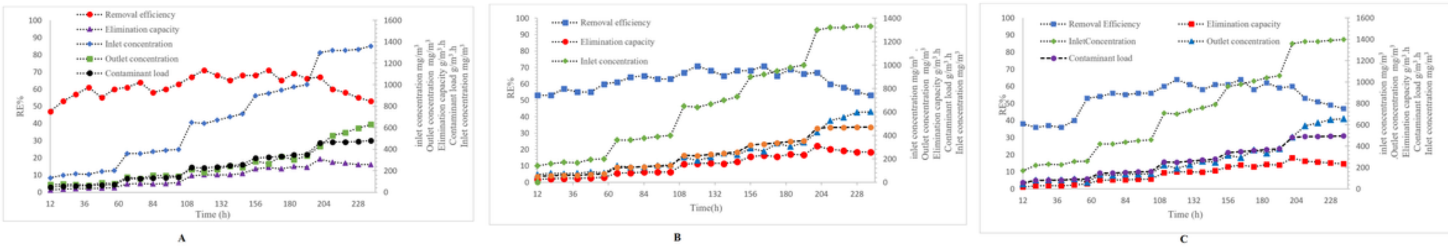

Figure 6

a Bioscrubber performance in toluene purification at 5% of cutting oil as organic phase

b Performance of bioscrubber in toluene purification at 7.5% of cutting oil as organic phase

c Bioscrubber performance in toluene purification at 10% of cutting oil as organic phase

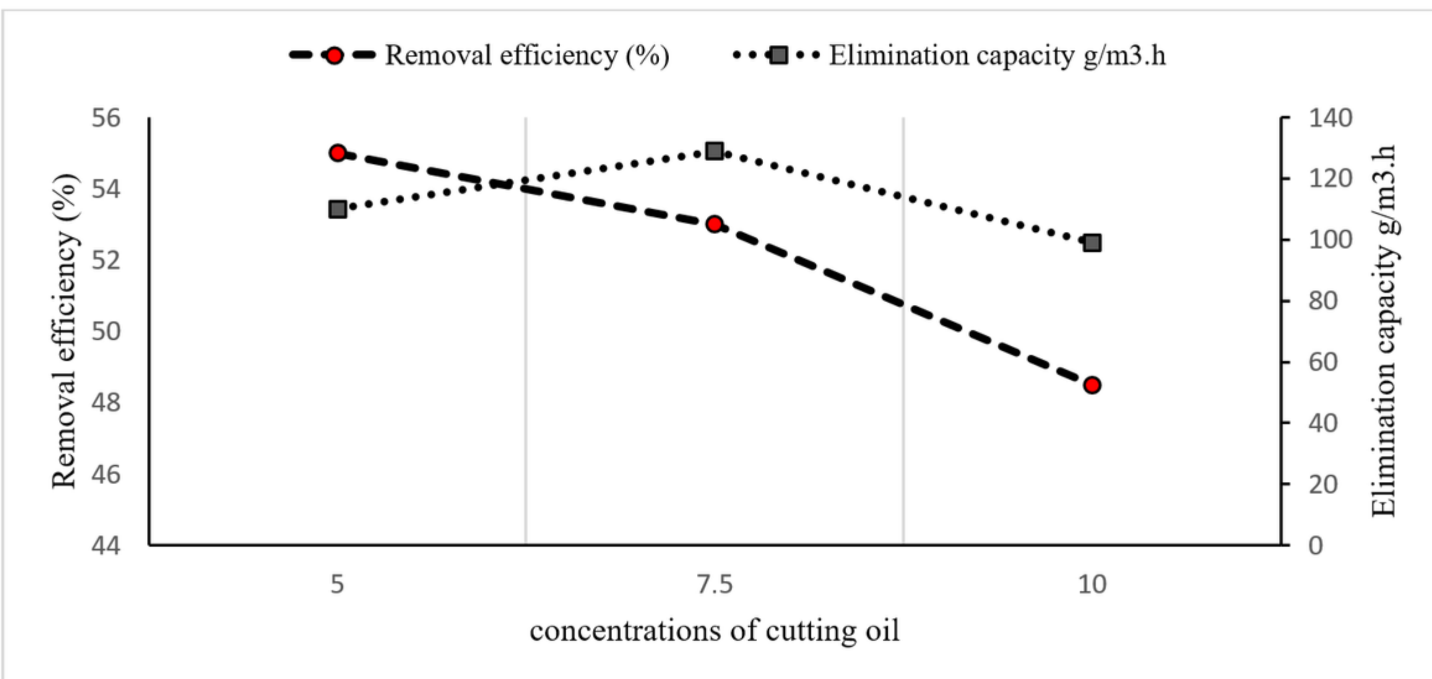

Figure 7

Comparison of removal efficiency and elimination capacity by three concentrations of cutting oil

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