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# INTERACTION OF ACRYLONITRILE VAPORS ON A BENCH SCALE BIOFILTER TREATING STYRENE-POLLUTED WASTE GAS STREAMS

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## ABSTRACT

Considering concurrent use of styrene and acrylonitrile as raw materials in the production of synthetic resins and plastic and their associated differences in physiochemical properties and biodegradability, our experiments were conducted in a three-stage downflow bench-scale biofilter to study the potential suppressive effects of acrylonitrile on styrene removal. A Mixture of yard waste compost and shredded plastics and activated sludge was used as bed media. Gas phase concentration of styrene and acrylonitrile was determined via gas chromatographic analysis. Under steady-state conditions, maximum elimination capacity of styrene and acrylonitrile was 44 and 120 g/m$^3$ h, respectively. The effect of moisture was very significant in reducing the specific adsorptive capacity (µg/g of bed media) of styrene and acrylonitrile. The bed media with 60% moisture content lost styrene absorption capacities by more than one order of magnitude when compared to dry media. The existence of water increased the absorption capacity of medium for acrylonitrile about 95%. Styrene elimination capacity of the biofilter during co-treatment was less as compared to pure styrene biodegradation indicating the likelihood of inhibitory kinetics. Introduction of acrylonitrile into the air stream reduced elimination capacity of styrene to 103 g/m$^3$ h. The adverse impact on removal rate of acrylonitrile due to the presence of styrene in the gas stream was minimal. Carbon-equivalent removal for the system amounted to about 85 g C/m$^3$ h at empty bed retention time of 120 s.

**Key words:** Styrene; Acrylonitrile; Co-treatment; Biodegradation; Biofiltration; Compost; Activated sludge

## INTRODUCTION

Most of the volatile organic compounds (VOCs) have been listed as human health toxics and must be removed from the working environment. Physicochemical process such as photocatalytic oxidation has been evaluated as an alternative technology for elimination of VOCs particularly at low concentrations (Rezaee, *et al*., 2008). Increased costs for chemicals and stricter hazardous waste disposal costs have provided necessary incentives for alternative treatment technologies of VOCs (Devinny *et al*., 1999). Biofiltration systems have become an increasingly attractive option for addressing this issue because of relative biodegradability of most VOCs (Ottangraf, 1986; Leson and Winer, 1991). Also biofiltration has been concluded as a reliable, economic and environmental friendly system to minimize inorganic compounds such as ammonia from waste gas streams (Shahmansouri *et al*., 2005).

This technology is most suitable for waste gas streams with low concentrations and high flow rates. In these systems, contaminated gas

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stream passes through a porous media fortified with immobilized microbial population. As the contaminated stream passes through the filter bed, pollutants are transferred from the gas phase to the biolayer by adsorption/absorption processes and followed by microbial degradation.

Langmuir and Freundlich isotherms are the most common models used for predicting adsorption performance in biofiltration and Henry law linear equation can be used to represent the absorption rate (Pagans *et al*., 2007). A large body of research data exists for biofiltration of VOC mixtures including oxygenated, aromatic, and halogenated compounds (Kinney *et al*. 1996; Quinlan *et al*., 1999; Kennes and Veiga, 2001). In contrast, more research is needed in the areas of synergistic and antagonistic effects of cotreating compounds commonly found in many industrial off gases (Garcia -Pena *et al*., 2008). Some researchers (Cai *et al*., 2007) have found that oxygenated VOCs were preferentially degraded in the presence of aromatic and halogenated VOCs while in another study inhibitory effect of methanol was reported on the removal rate of α-pinene in wood-chip biofilter (Mohseni and Allen, 2000). Evaluation the inhibitory effect of ethyl acetate and toluene as mixed substrate showed that toluene degradation was inhibited in the presence of ethyl acetate but the removal efficiency of ethyl acetate in the presence of toluene was not affected (Alvarez-Hornos *et al*., 2007).

Styrene monomers along with acrylonitrile are used to make a host of downstream consumer products including polystyrene, expandable polystyrene and acrylonitrile-butadiene-styrene and styrene-acrylonitrile resins, styrene butadiene latex and rubber, unsaturated polyester resins, styrene thermoplastic elastomers, nitrile rubbers, carbon fibers and acrylamide. Styrene and acrylonitrile are among the toxics cited under Title III of 1990 Clean Air Act Amendments (USEPA, 1993 and 1999). The greatest human exposure to styrene and acrylonitrile occurs among workers during raw material production. Epidemiological studies have not proved definite association between styrene and any forms of cancer in humans yet but styrene and acrylonitrile have been cited as possible human carcinogen (Cole *et al*., 2008; Rueff *et al*., 2009).

Whereas biological treatment of gas stream contaminated with dilute concentrations of styrene has become a proven technology (Arnold *et al*., 1997; Chou and Hsiao, 1998; Pol *et al*., 1998; Jorio *et al*., 2000; Juneson *et al*., 2001; Paca *et al*., 2001; Zilli *et al*., 2001; Zilli *et al*., 2003), information on the biodegradability of acrylonitrile with a mixed culture needs further research (Li *et al*. 2007). Lu *et al.* reported up to 95% removal efficiency at acrylonitrile loading range of 3 to 490 g/m$^3$ h (Lu *et al*., 2001; Lu *et al*., 2002).

The main objective of this research was to evaluate the performance of biofiltration process in treatment of styrene and studying inhibitory effect of acrylonitrile as a co-substrate on styrene elimination. Since acrylonitrile is regarded as hydrophilic and styrene a nearly hydrophobic hydrocarbon, investigation of the inhibitory effects was regarded as necessary considering their co presence in off gases which are used as raw materials in the plastic manufacturing processes.

## MATERIALS AND METHODS

### *Experimental set up*

A three-stage downflow bench-scale biofilter was used for removal of styrene and acrylonitrile mixture from a synthetic gas stream. The galvanized iron biofilter (Fig. 1) had an inner diameter of 8 cm with an effective bed height of 120 cm. Perforated steel plate plenums (pore diameter = 2 mm) placed between sections acted as support for the packing material as well as for gas flow redistribution. A 7-cm height space in between the sections allowed for representative gas sampling. Provision of sampling ports at the top, midpoint, and the end of each section allowed bed media access. The waste gas stream was prepared by passing compressed air through a granular activated carbon canister to capture residual oil and particles. The gas was then sparged through a 15 L water container equipped with heated element for stream temperature adjustment and humidification. Pollutant vapor was prepared by introducing low flow air stream into a container receiving drop-wise styrene and acrylonitrile feed from separate burettes. The main clean air stream was mixed with the stream containing pollutant vapor to generate feed air with the needed concentration. Temperature control of the bed material to 30±1°C was achieved by using a heated tape wrapped around the exterior of the reactor wall. Water content of the bed material was maintained at 60-65% during the study period.

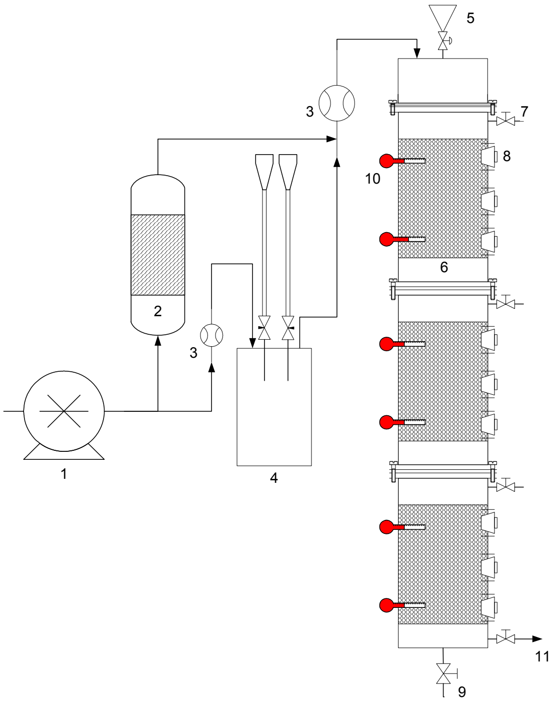

Fig. 1: Schematics of biofilter system: 1-compressor, 2-humidifier, 3- air flowmeter, 4-styrene and acrylonitrile injector, 5-nutrient inlet, 6- biofilter bed, 7-gas sampling port, 8-bed sampling port, 9-leachate outlet, 10-thermometer, 11-clean air outlet

### *Filter bed material*

Bed media was prepared by mixing yard waste compost and shredded 1-0.5-0.1 cm poly vinyl chloride (PVC) as bulking agent with a plastic:compost ratio of about 25:75 v/v and an overall porosity of 54%. Thickened activated sludge obtained from municipal wastewater treatment plant was added to this mixture to increase microbial density and improve homogeneity of compost particles and bulking agents. Nutrient and buffering solution was added to the bed medium to keep the C:N:P ratio around 100:5:1. The nutrient solution had the following composition (per liter of tap water): 0.694 g $KH_2PO_4$, 0.854 g $K_2HPO_4$, 1.234 g $(NH_4)_2SO_4$, 0.46 g $MgSO_4.H_2O$, 0.176 g $CaCl_2.2H_2O$, 0.001 g $FeSO_4.7H_2O$, and 5 mL trace element solution consisting of 60 mg/L $H_3BO_3$, 40 mg$CoCl_2.6H_2O$, 20 mg/L $ZnSO_4.7H_2O$, 6 mg/L $MnCl_2.4H_2O$, 6 mg/L $NaMoO_4.2H_2O$, 4 mg/L $NiCl_2.6H_2O$, 2 mg/L $CuCl_2.2H_2O$ with an overall pH around 6.9 ± 2(Ergas *et al*., 1994).

### *Analytical methods*

Gas phase concentrations of styrene and acrylonitrile was determined via gas chromatographic (model SRI 110 Inc., USA) analysis. The gas chromatograph was equipped with a flame ionization detector and a 30 m stainless steel 3 % SP-1500 80/120 Carbopack capillary column. Operating conditions were as follows: temperature schedule (injector 200 ºC, oven with initial temperature of 100 ºC and ramp of 40 ºC per min to reach the final temperature of 220 ºC with holding time of 0.1 min and detector temperature of 230 ºC) and $N_2$ carrier gas at 8 mL/min, $H_2$ as makeup gas with flow rate of 25 mL/min and $O_2$ in 6 mL/min flow rate. The gas chromatograph was calibrated for styrene concentrations ranging from zero to about 1 g/m$^3$ and for acrylonitrile concentrations from zero to 2.5 g/m$^3$ to plot the calibration curves. The reproducibility of the GC output was determined by replicate styrene and acrylonitrile measurements. Average standard deviation for the GC was about 5% and 8% at very low concentrations of styrene and acrylonitrile, respectively. Biotransformation of the VOCs was distinguished from physiochemical adsorption by analyzing dry and moist sterilized bed material sorption capacity.

## RESULTS

The adsorption and absorption capacities of dry and moist mixture of PVC shreds, compost and activated sludge for styrene and acrylonitrile are shown in Fig. 2. At this period of experiment the biofilter operated with constant empty bed retention time (EBRT) of 60 s. The effect of moisture was very significant in reducing the specific adsorptive capacity (µg/g of bed media) of styrene and acrylonitrile. Maximum adsorption/

absorption capacities of about 14 and 99 µg/g of dry and wet bed media were obtained for styrene and acrylonitrile, respectively.

In two periods over the course of this experiment, the biofilter was run without acrylonitrile (with only styrene) and vice versa in order to study the response of the biofilter to the changes in the nature of the pollutants.

Actually the main course of experiments was initiated in a biofilter used to treat styrene vapor for more than one year (Dehghanzadeh *et al.*, 2005). The biofilter has already been operated at different organic loading rates by changing styrene inlet concentration from 0.2 to 2.5 g/m$^3$. Styrene loading rates between 5 and 45 g/m$^3$h resulted steady state removal efficiency close to 96 ± 1%. However for higher organic loading rates of about 60 and 75 g/m$^3$h, the removal efficiency decreased to 74 ± 1% and 58 ± 1%, respectively. Finally with EBRT of 60 s, maximum removal efficiency of about 97% was obtained at inlet concentration of 0.2 g/m$^3$ corresponding to styrene loading rate of 12 g/m$^3$ h.

As Shown on Fig. 3 at the start up of the experiment, styrene inlet concentration was maintained at about 0.5 g/m$^3$ and thereafter acrylonitrile was injected with concentration of about 0.4 g /m$^3$. EBRT of the biofilter was kept at 120 s. The removal of acrylonitrile was increased to more than 80% in 10 day and close to 95% after about 20 day. The removal efficiency of styrene after introducing acrylonitrile into the gas stream was decreased from 100% to about 80%. However, after elimination of acrylonitrile from the inlet gas stream removal efficiency of styrene was increased gradually to about 95%. When the acrylonitrile addition was recommenced after a relatively long period of operation with styrene solely, the biofilter recovered within a few hours and the removal efficiency of acrylonitrile reached to its previous value of about 95%. Also, during the experiment, styrene was eliminated from the air stream and the biofilter was run with only acrylonitrile which showed any more fluctuation in its removal efficiency.

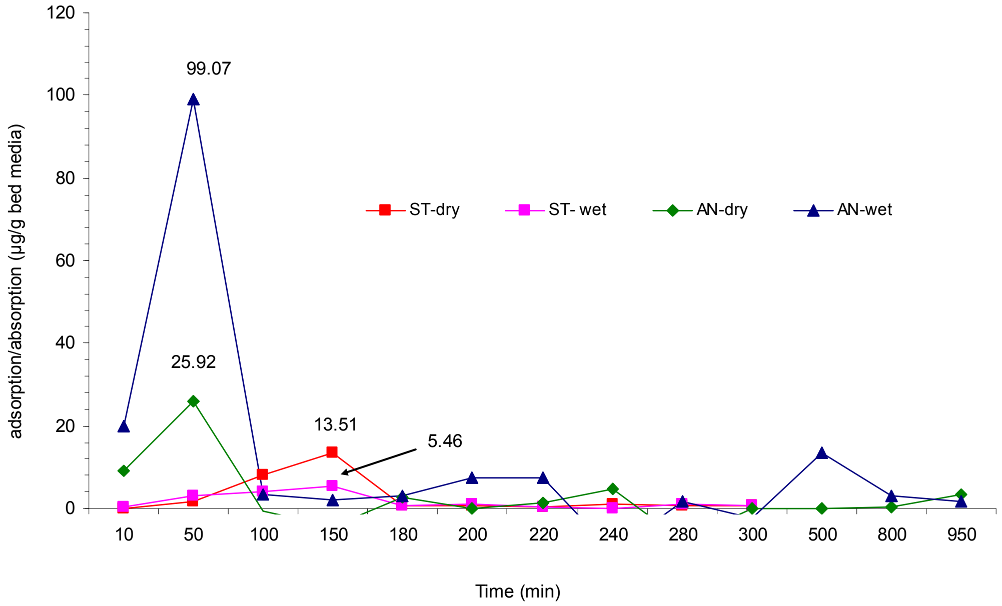

Fig. 2: Determination of styrene (ST) and acrylonitrile (AN) sorption on compost based media (EBRT = 60 s and T= 30°C)

After start up period, the performance of biofilter was more evaluated at EBRTs of 60 and 30 s. In the period of the experiment styrene inlet concentration was ranged between 0.42 and 0.98 g/m$^3$ and acrylonitrile inlet concentration was constantly increased from 0.41 to 2.52 g /m$^3$. With the above operation condition the biofilter provided acrylonitrile removals of about 19-103 and 59-68 g/m$^3$h at EBRTs of 60 and 30 s, respectively. The maximum styrene removal was achieved when acrylonitrile was absent in the air stream on days 46 through 62. On days 93 to 151 the styrene loading rate was kept at constant rate of about 35 g/m$^3$h, but acrylonitrile loading rate increased from 50 to 110 g/m$^3$h which resulted decrease of styrene removal efficiency from 67% to 40%.

Concentration profiles of styrene and acrylonitrile along the biofilter column was also monitored. As shown in Fig. 4, acrylonitrile was removed preferentially in the top sections of the biofilter. Higher acrylonitrile removal was observed in the entry section in the beginning of the experiments (day 4), possibly due to physical absorption.

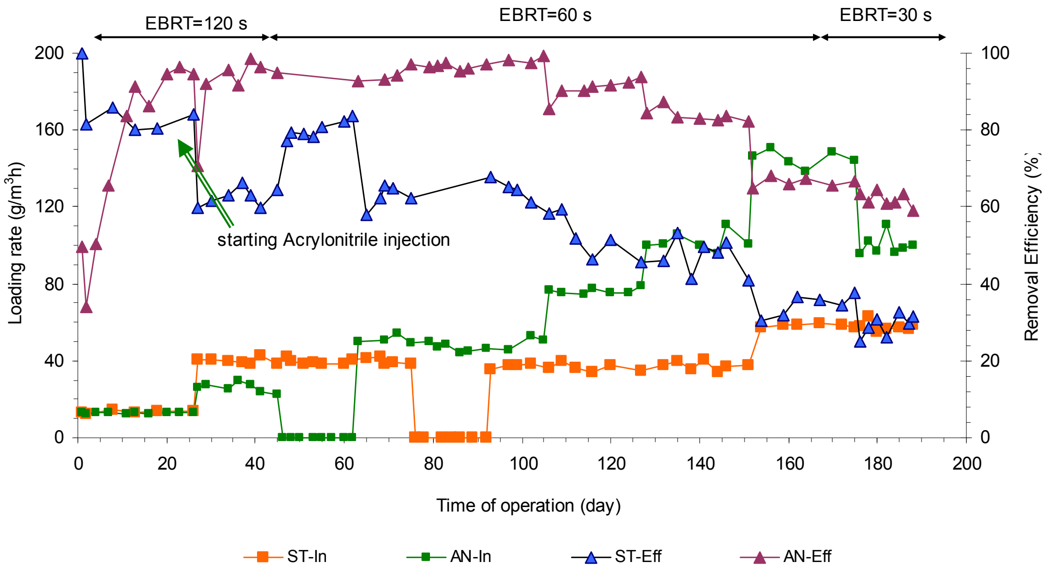

Fig. 3: Overall performance of biofilter in co-treatment of styrene and acrylonitrile vapors

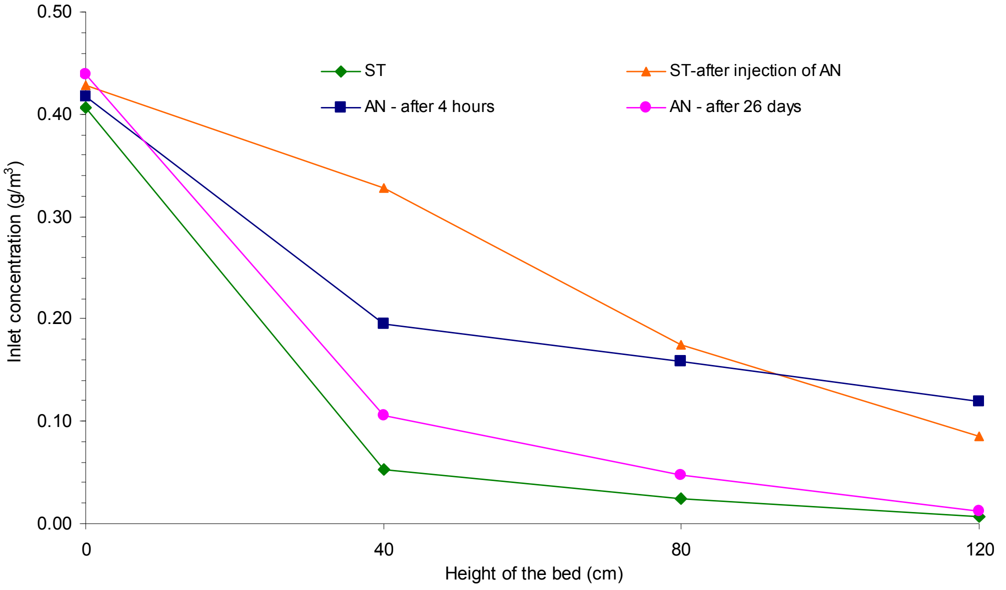

Fig. 4: Concentration profiles at start up period for simultaneous treatment of styrene (ST) and acrylonitrile (AN)

Results from day seven showed an increased removal rate, indicating adaptation of the microbial population.

Fig. 5 shows the overall performance of the biofilter in removing styrene and acrylonitrile in terms of total carbon loadings. The biofilter removed up to about 85 g carbon/m$^3$h at EBRTs between 30 and 120 s. Removal efficiency of the biofilter was near to 100 % up to the carbon loading rate of 40 g/m$^3$ h. Maximum elimination capacity of biofilter for removal of styrene and acrylonitrile mixture was obtained about 80 g/m$^3$h at 150 g/m$^3$ h of total carbon loading rate.

At steady-state condition, concentration gradient for styrene and acrylonitrile mixture along the biofilter column is illustrated in Fig. 6. During the biofiltration of pure styrene and with inlet concentration of 0.6 g/m$^3$ more than 50 % of

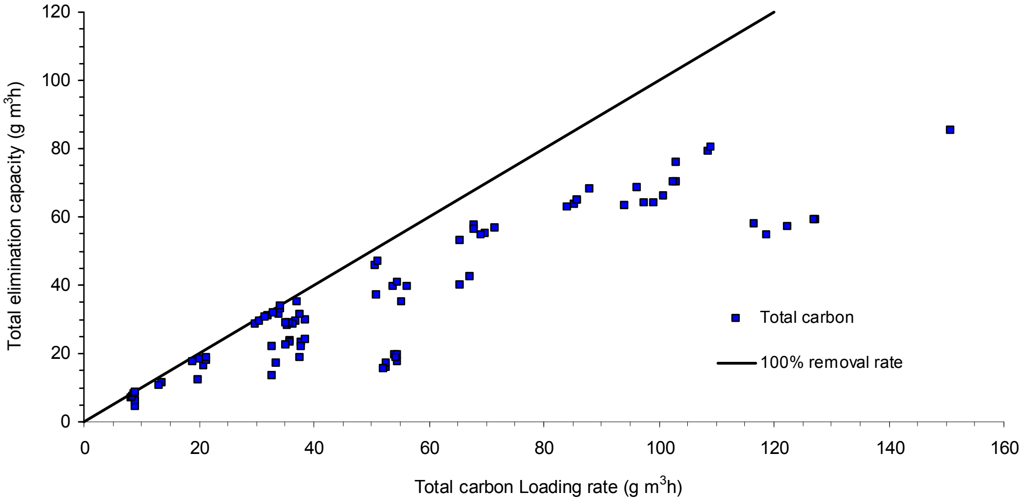

Fig. 5: Overall performance of biofilter in treating total inlet organic carbon

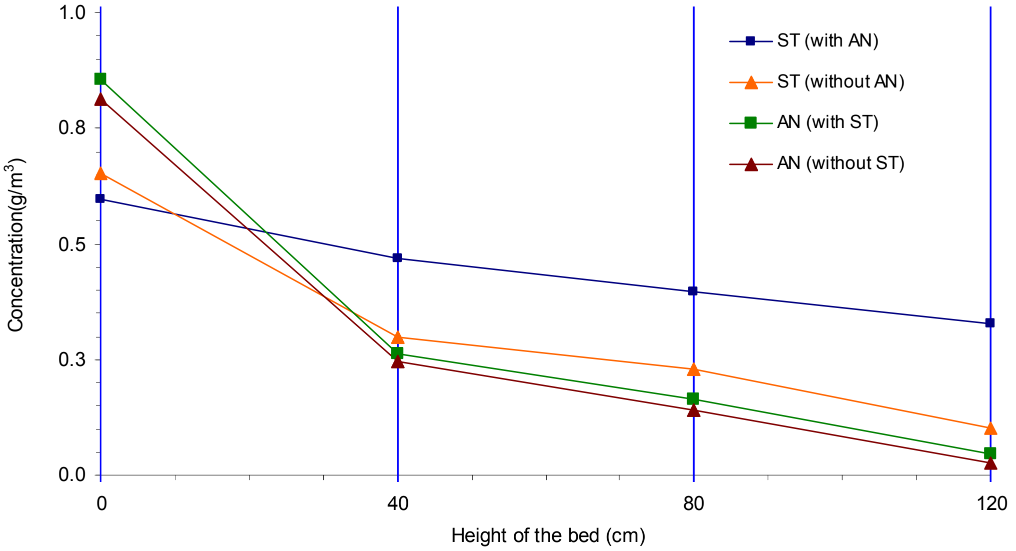

Fig. 6: Concentration profile along the bed height of the biofilter in co-treatment of acrylonitrile (AN) and styrene (ST)at EBRT of 60 s

styrene was removed at the first section of biofilter column. While adding of acrylonitrile to the styrene laden gas stream performed 20 % and 70 % removal of the influent styrene and acrylonitrile, respectively, in the first section of the biofilter. Present or absent of styrene did not show significant deviation in the concentration profile of pure acrylonitrile. There was complete biodegradation of styrene before introducing of acrylonitrile throughout the biofilter, but the concentration profile of styrene along the biofilter came up in the following days.

Fig. 7 shows the elimination capacity (EC) of styrene in absence of acrylonitrile and concurrent with acrylonitrile. Maximum elimination capacity of 103 g/m$^3$h for acrylonitrile occurred at EBRT of 60 s corresponding to removal efficiency of about 70%. At loading rates up to 80 g /m$^3$h, the biofilter performed complete degradation of acrylonitrile and removal efficiency of biofilter increased gradually. Signs of declined activity started to appear at higher loading rates reaching to constant level at about 100 g/m$^3$ h. Also acrylonitrile elimination capacity was dependent to inlet concentration and progressively increased up to 1.85 g/m$^3$. In the continuation of the work, maximum elimination capacity of styrene reported was 34 g/m$^3$h corresponding to inlet concentration of about 0.6 g/m$^3$ at acrylonitrile concentrations lower than 0.75 g/m$^3$.

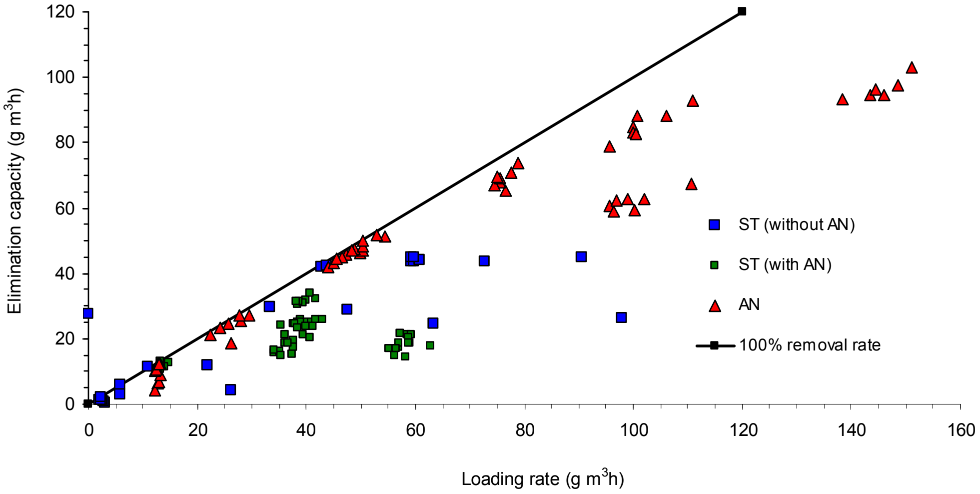

Fig. 7: Effect of loading rate variations on elimination of styrene (ST) and acrylonitrile (AN) mixture.

## DISCUSSION

Adsorption and absorption phenomena have an important function in biofilter performance and performs buffer characteristic for biological activity during transient conditions and shock loadings (Barona *et al*., 2005; Mcnevin and Barford, 2001). On the other hand, absorption is a predominant mechanism in the transfer of pollutants from gas phase to the biofilm especially for compounds with higher solubility in water. The bed media with 60% moisture content lost styrene absorption capacities by more than one order of magnitude when compared to dry media. Also existence of water increased the absorption capacity of medium for acrylonitrile to about 95% and wet media has showed about five orders of magnitude greater absorption capacity for acrylonitrile than styrene. This is in contrast to the results reported by the other researchers indicating that the water content of the peat did not have a significant effect on the adsorption of the hydrophobic compounds (Acuna *et al*. 1999).

Estimated breakthrough time of styrene and acrylonitrile corresponding to inlet concentrations of about 2.06 and 1.26 g/m$^3$ and at 30 °C were lower than 150 and 50 min both with dry and wet bed, respectively. Acuna *et al*. (1999) reported adsorption of 459 µg toluene per g of dry peat and 137 µg per g of moist peat that was higher than the values of 22.5 µg per g of dry mixture of peat-perlite reported by Baltzis and Shareefdeen (1994) which may be due to the high organic content of the pure peat.

During the start up period, gradual decline of styrene removal was observed upon introduction of acrylonitrile into the gas stream indicating suppression of styrene degrading microorganisms in presence of hydrophilic and more easily biodegradable acrylonitrile. This effect was more observed at higher acrylonitrile inlet concentrations. According to the results of this experiment, when the elimination capacities of mixed VOC are compared with those for a pure VOC in the literature, it was found that with similar carbon loading rates the elimination capacities for a pure VOC feed were significantly higher than those for a mixed VOC feed. However, the results cannot be directly compared to those obtained for either hydrophobic or hydrophilic VOCs. Nonetheless, the overall VOC removal rate in this study is comparable to and or higher than the results obtained by other researchers (e.g. Mehrdadi, *et al*., 2010; Deshusses and Johnson, 2000; Baltzis *et al*., 1997; Govind *et al*., 1993; Shareefdeen *et al*., 1993) working on single and/ or mixed VOCs. Also in comparing with the data of this paper, Lu and Chang, (2004) reported that butylacetate is a preferred substrate to the microorganisms when butylacetate and xylene mixture are feed to the biofilter. Alvarez-Hornos, *et al*. (2007) reported that ethylacetate is more easily biodegradable compound than toluene and the presence of ethylacetate reduced the removal of toluene in a peat bed biofilter. Mohseni and Allen (2000) reported maximum 80 g carbon/m$^3$ h at EBRT of 30s on the removal of α-pinene and methanol mixture. The higher removal rate in this work may be the result of mixed cultures used in bed inoculation, availability of inorganic nutrients and bed moisture and temperature (Torkian *et al*., 2003). Higher EC for styrene when it is the sole carbon source can be contributed to the competition for the biotransformation activity among co-substrates in metabolic reactions. The difference in the elimination capacity of the pure and mixed VOCs was more intense with increasing organic loading rates.

Since acrylonitrile is water soluble and easily biodegradable, as much as 70% removal is observed in the top section of the bed. This is accordance with the results reported in the biofiltration of triethylamine by a compost based biofilter where more than 75% of inlet concentration removed in the first section of biofilter (Torkian *et al*., 2005). Zilli *et al*. (2003) showed that at relatively low inlet styrene concentrations of about 0.4 g/m$^3$, biomass concentration reached a maximum value at the first section and decreased incrementally along the column regardless of the EBRT due to the gradually decrease in styrene availability.

The biofilter performance did not seem to be affected as a result of introducing styrene in the air stream. However, the presence of acrylonitrile in the air stream significantly influenced the removal of styrene to the extent that there was little styrene removal in the top section where acrylonitrile was being degraded. Biodegradation rate of styrene increased in the lower sections of the biofilter where acrylonitrile concentration was minimal. This implies a degree of inhibitory kinetics for the assimilation of styrene in that its removal rate is affected by the introduction of acrylonitrile vapor into the microbial community. Also, the complete removal of acrylonitrile in the top section of the biofilter suggests that the overall biofilter system has a much larger capacity for treating acrylonitrile. Overally, under steady-state condition and where both VOCs were present, the total styrene removal capacity of the biofilter was less than what was observed in the biofiltration of pure styrene (Dehghanzadeh *et al*., 2005).

At acrylonitrile inlet concentrations higher than 0.75 g/m$^3$, styrene removal rate showed signs of decline in comparison to pure styrene treatment. In an identical work, it has been reported that at butylacetate inlet concentrations of greater than 0.2 g/m$^3$, the removal efficiency of styrene dropped by about 50% (McGrath *et al*., 1999). Also in another work it has been shown that competitive inhibition from ethylacetate assimilation would affect the toluene degradation efficiency (Deshusses and Johnson, 2000)**.**

It is therefore concluded that biofiltration is a feasible air pollution control technology and can achieve relatively high *VOC* elimination capacities if it is appropriately designed and all the important parameters are properly controlled. Therefore for elimination of VOCs from any waste gas flow emitted from industrial processes, conducting pilot plant experiments is necessary before any scale up of this technology to obtain design criteria and recognize operational parameters.

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## REFERENCES

Acuna, M. E., F. Perez, F., Auria, R., Revah, S., (1999). Microbiological and kinetic aspects of a biofilter for the removal of toluene from waste gases. Biotechnol Bioeng, **63**(2): 175-84.

Alvarez-Hornos, F. J., Gabaldon, C., Soria, M. V., Marzal, P., Roja, P. J. M., Izquierdo, M., (2007). Long-term performance of peat biofilters treating ethyl acetate, toluene, and its mixture in air. Biotechnol Bioeng, **96**(4): 651-60.

Arnold, M., Reittu, A.,Von Wright, A., Martikainen, P. J., Suihko, M. L., (1997). Bacterial degradation of styrene in waste gases using a peat filter. Appl Microbiol Biotechnol, **48**(6): 738-44.

Baltzis, B. C., and Shareefdeen, Z., (1994). Biofiltration of VOC mixtures: modeling and pilot scale experimental verification. In 87th Annual Meeting & Exhibition Air & Waste Management Assoc., Cincinnati, Ohio, A907.

Baltzis, B. C. S., Wojdyla, M., Zarook, S. M., (1997). Modeling biofiltration of VOC mixtures under steady-state conditions. J. Environ. Eng, **123**: 7.

Barona, A., Elý´as, A., Amurrio, A., Cano, I., Arias, R., (2005). Hydrogen sulphide adsorption on a waste material used in bioreactors. Biochemical Eng J, **24**:79–86.

Cai, Z., Kim, D., Soria, L. G. A., (2007). A comparative study in treating two VOC mixtures in trickle bed air biofilters. Chemosphere, **68**(6): 1090-7.

Chou, M. S., and Hsiao, C. C., (1998). Treatment of styrene-contaminated airstreams in biotrickling filter packed with slag. J. Environ. Eng, **124**: 7.

Cole, P., Mandel, J. S. Collins, J. J., (2008). Acrylonitrile and cancer: a review of the epidemiology. Regul Toxicol Pharmacol, **52**(3): 342-51.

Dehghanzadeh, R., Torkian, A., Bina, B., Poormoghaddas, H., Kalantary, A., (2005). Biodegradation of styrene laden waste gas stream using a compost-based biofilter. Chemosphere, **60**(3): 434-9.

Deshusses, A. and Johnson, C. T., (2000). Development and validation of a simple protocol to rapidly determine the performance of biofilters for VOC treatment. Environ. Sci. Technol, **34**: 7.

Devinny, J. S., Deshusess, M. A., Webster, T. S., (1999). Biofiltration for air pollution control. Lewis Publisher, CRC press, Bocca Raton, USA.

Ergas, S. J., Kinney, K., Fuller, M. E., Scow, K. M., (1994). Characterization of compost biofiltration system degrading dichloromethane. Biotechnol Bioeng, **44**(9): 1048-54.

Garcia -Pena, I., Ortiz, I., Hernandez, S., Revah, S., (2008). Biofiltration of BTEX by the fungus Paecilomyces variotii. Int. Biodeterior. Biodegradation, **62**: 6.

Govind, R., Utgikar, V., Zhao, W., Shan, Y., Parvatiar, M., (1993). Development of novel biofilters for the treatment of volatile organic compounds. Proceeding of IGT Symposium on Gas, Oil, and Environmental Biotechnology, Colorado Springs, USA.

Jorio, H., Bibeau, L., Heitz, M., (2000). Biofiltration of air contaminated by styrene: effect of nitrogen supply gas flow rate, and inlet concentration. Environ. Sci. Technol, **34**: 8.

Juneson, C., O., Ward, P., Singh, A., (2001). Microbial treatment of a styrene-contaminated air stream in a biofilter with high elimination capacities. J Ind Microbiol Biotechnol, **26**(4): 196-202.

Kennes, C., and Veiga, M. C., (2001). Bioreactors for waste gas treatment, Kluwer Academic Publishers: Boston, USA.

Kinney, K. A., du Plessis, C., Schroeder, E. D., Chang, D., Scow, K. M., (1996). Optimizing microbial activity in a directionally-switching biofilter. In Proceedings of the USC-TRG Conference on Biofiltration, Los Angeles, University of Southern California, USA.

Leson, G., and Winer, A. M., (1991). Biofiltration: an innovative air pollution control technology for VOC emissions. J Air Waste Manage Assoc, **41**(8): 1045-54.

Li, T., Liu, J., Bai, R., Ohandja, D., Wong, F., (2007). Biodegradation of organonitriles by adapted activated sludge consortium with acetonitrile-degrading microorganisms. Water Res, **41**(15): 3465-73.

Lu, C., and Chang, K., (2004). Biofiltration of Butylacetate and Xylene mixtures using a trickel- bed air biofilter. Eng. Life Sci, **4**(2): 131-137

Lu, C., Lin, M. R. Lin, J., (2001). Removal of styrene vapor from waste gases by a trickle-bed air biofilter. J Hazard Mater, **82**(3): 233-45.

Lu, C., Lin, M. R., Wey, R., (2002). Removal of acrylonitrile and styrene mixtures from waste gases by a trickle-bed air biofilter. Bioprocess Biosyst Eng, **25**(1): 61-7.

McGrath, M., Nieuwland, J., van Lith, C., (1999). Biofiltration of styrene and butylacetate at a dashboard manufacturer. Environ Prog, **18**: 8.

Mcnevin, D., and Barford, J., (2001). Inter-relationship between adsorption and pH in peat biofilters in the context of a cation-exchange mechanism.» Water Res, **35**:736–744.

Mehrdadi, N, Keshavarzi Shirazi, H., Azimi, A. A., Mirmohammadi M., (2010)**.** Removal of Triethylamine vapor from waste gases by biotrickling filter**.”** Iran J Environ Health Sci Eng, **7**(4):337-344.

Mohseni, M., and Allen, D. G., (2000). Biofiltration of mixtures of hydrophilic and hydrophobic volatile organic compounds. Chem. Eng. Sci, **55**: 14.

Ottangraf, S. P. P., (1986). Exhast gas purification. Biotechnology, Rem, H.J., Reed, G., Eds.; Verlagsgesellschaft (VCH): Weinheim, Germany, **8**: 28.

Paca, J., Koutsky, B.,Maryska, M., Halecky, M., (2001). Styrene degradation along the bed height of Perlite biofilter. J. Chem. Technol. Biotechnol, **76**: 6.

Pagans, E., Font, X., Sanchez, A., (2007). Adsorption, absorption, and biological degradation of ammonia in different biofilter organic media. Biotechnol Bioeng, **97**(3): 515-25.

Pol, A., van Haren, F. J. J., op den Camp, H.J.M., van der Drift, C., (1998). Styrene removal from waste gas with a bacterial biotrickling filter. Biotechnol. Lett, **20**: 4.

Quinlan, C., Strevett, K., Ketchman, M., Grego, J., (1999). VOC elimination in a compost biofilter using a previously acclimated bacterial inoculum. J Air Waste Manag Assoc, **49**(5): 544-53.

Rezaee, A., Pourtaghi, Gh. H., Khavanin, A., Sarraf Mamoory, R., Ghaneian, M. T., Godini, H., (2008). Photocatalytic decomposition of gaseous toluene by TiO2 nanoparticles coated on activated carbon. Iran J Environ Health Sci Eng, **5**(4): 305-310

Rueff, J., Teixeira, J. P., Santos, L.S., Gaspar, J. F., (2009). Genetic effects and biotoxicity monitoring of occupational styrene exposure. Clin Chim Acta, **399**(1-2): 8-23.

Shahmansouri, M. R., Taghipour, H., Bina, B., Movahedian, H., (2005). Biological removal of ammonia from contaminated air streams using biofiltration system. Iran J Environ Health Sci Eng, **2**(2):17-25.

Shareefdeen, Z., Baltzis, B. C., Oh, Y. S., Bartha, R., (1993). Biofiltration of methanol vapor. Biotechnol Bioeng, **41**(5): 512-24.

Torkian, A., Dehghanzadeh, R., Hakimjavadi, M., (2003). Biodegradation of aromatic hydrocarbons in a compost biofilter. J. Chem. Technol. Biotechnol, **78**: 7.

Torkian, A., Keshavarzi Shirazi, H., Azimi, A., (2005). Effects of operational conditions on the performance of Triethylamine biofiltration. Iran J Environ Health Sci Eng, **2**(2):31-40

United state Environmental Protection Agency (USEPA), (1993). Integrated Risk Information System (IRIS) on acrylonitrile. National Center for Environmental Assessment, Office of Research and Development, Cincinnati, OH, USA,.

United state Environmental Protection Agency (USEPA), (1999). Integrated Risk Information System (IRIS) on Styrene. National Center for Environmental Assessment, Office of Research and Development, Washington DC, USA.

Zilli, M., Converti, A., di Felice, R., (2003). Macrokinetic and quantitative microbial investigation on a bench-scale biofilter treating styrene-polluted gaseous streams. Biotechnol Bioeng, **83**(1): 29-38.

Zilli, M., Palazzi, E., Sene, L., Converti, A., del Borghi, M., (2001). Toluene and styrene removal from air in biofilters. Process. Biochemistry, **37**: 7.