Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.854102

52 (2014) 3600–3615
May

Taylor & Francis
Taylor & Francis Group

Biofiltration process as an ideal approach to remove pollutants from polluted air

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Received 21 March 2013; Accepted 20 September 2013

ABSTRACT

Most developing and developed countries are facing the problems and challenges of air pollution. Many governments have enacted laws and policies to enforce industrial activities to reduce air contaminating emissions and are mainly carried out by installation of air pollution control systems. Therefore, the use of suitable technique such as biofiltration processes to control air pollutants is necessary. Although many studies have been published on the designing and operations of polluted air treatment using biofiltration processes but a comprehensive review on it is still lacking. Till now due to conceptual designing and operational knowledge, several cases of failure or sub-optimum designing has been reported about the use of biofiltration process to treat polluted air. This paper presents a comprehensive review of biofiltration processes and technology for the control of organic and inorganic pollutants as an ideal approach to remove pollutants from polluted air. It also covers classification, functional mechanism, designing, and its operational parameters to treat polluted air. Comprehensive literature review suggests that the use of bio-trickling filter processes to treat polluted air can help to create excellent design and optimum operation to generate pollution free environment. In conclusion, the paper outlines designing, function, and operation of biofiltration process.

Keywords: Air pollutant; Biofiltration process; Designing; Operation; Biological treatment

1. Introduction

The current situation and the laws enforced by the environmental body have made strong and positive influence on new technologies toward better treatment of polluted air. Air treatment techniques can be divided into four categories: chemical, physical, biological, and biochemical methods (mix methods or multistage air treatment systems are a combination of chemical and biological methods). This categorization is shown in Fig. 1.

Many methods have been developed to treat polluted air such as wet scrubber, incinerator,

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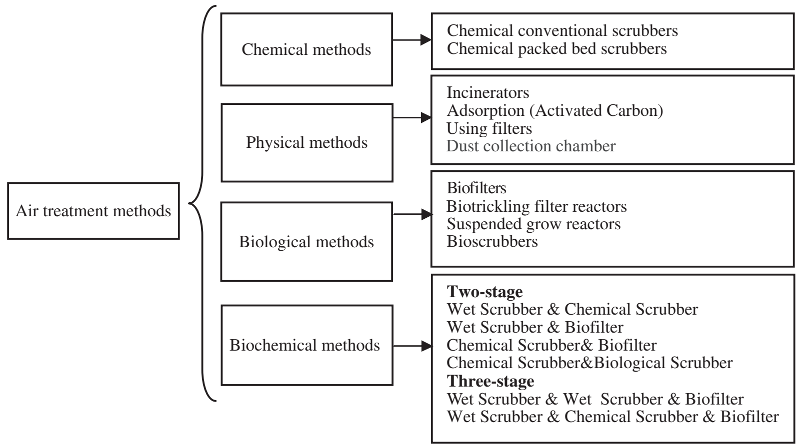

Fig. 1. Classification of air treatment methods.

adsorption on active carbon, biofilters (BFs), and biotrickling filters. Wet scrubbers are effective air pollution control devices for removing particles and/or gases from industrial exhaust streams. Wet scrubbers operate by introducing dirty polluted air stream with a scrubbing liquid—typically water. Particulate or gases are collected in the scrubbing liquid. Wet scrubbers are generally one of the most appropriate air pollution control device for collecting both particulate and gas in a single system. Wet scrubbers can also be used for heat recovery from hot gases. Removal efficiency of pollutants is improved by increasing residence time in the scrubber or by the increase of surface area of the scrubber solution by the use of a spray nozzle or packed towers. Wet scrubbers have suitable removal efficiency (RE). However, wet scrubbers generate significant amounts of wastewater that it need to treat again and that is why researchers are looking for new methods to treat polluted air. Another method to treat polluted air is by the use of incinerators. Incinerators operate by introducing the air contaminated with organic pollutants. Organic pollutants can be completely converted to carbon dioxide and water due to high temperature. Usually, high temperatures between 870 and 1,200˚C are used in the incinerators to complete the removal of pollutants from air. Incinerators are effective to remove odor and organic pollutants from polluted air. However, they are very energy consuming and they generate significant amounts of new waste products such as carbon dioxide. Adsorption of pollutants using activated carbon is another method to treat polluted air. Activated carbon is the universal standard applied for purification and removal of trace organic contaminants from liquid and vapor streams. Carbon adsorption uses activated carbon to control and/or recover gaseous pollutant emissions. In carbon adsorption, the gas is attracted and adheres to the porous surface of the activated carbon. Removal efficiencies of 95–99% can be achieved by using this process. Carbon adsorption is used in cases where the recovered organics are valuable. For example, carbon adsorption is often used to recover perchloroethylene, a compound used in the dry cleaning process.

Biological treatment methods applied to treat polluted air are environmentally friendly and do not generate NO_x, SO_x, or secondary pollutants. The biofiltration processes have been in use for several years to treat waste air with low concentrations of pollutants. Odor removal from polluted air is a classical example of biofiltration processes. Biofiltration process can remove odor from polluted air up to 99%. Biofiltration process has also been increasingly applied to treat volatile organic compounds (VOCs) in the polluted air of factories. The ability of the biofiltration process to treat polluted air with low concentration of pollutants and high volume of polluted air makes it a cost effective method to remove VOCs. In a biofiltration process, micro-organisms usually attach on the supporting materials through which the polluted air passes. Micro-organisms are able to consume contaminants present in the air. These contaminants are converted to water and carbon dioxide by microbial metabolisms. Some important factors, such as pH, temperature, gaseous retention time, etc. have important effect on biofiltration processes and have to be in optimum condition to achieve higher efficiency. Biofiltration technology can completely remove pollutants under optimum condition and are useful to treat larger volume of polluted air with concentration of VOC less than $3\,g/m^3$ [1]. Till date, the biofiltration processes have been applied worldwide to remove VOCs from polluted air; it is these environment friendly technologies that have good capability to remove VOCs without producing any negative by-products [2–4]. Groenestijn and Kraakman [5] reported that more than 7,500 reactors based on biofiltration process have been installed in European countries to treat polluted air, about half of them are used to remove odor from the wastewater. Some biofiltration processes are very simple, for example, a mass of soil can be a BF.

According to Mudliar et al. [6], despite the increase in number of full-scale treatment systems using biofiltration approach it seems that there is lack of sufficient information about such methods. There is no comprehensive review about biofiltration processes. Therefore, this review presents an overview of biofiltration processes and technologies for the control of organic and inorganic air pollutants. This works also presents classification, functioning mechanism, designing, and operational parameters to treat polluted air.

2. Overview of the bio-filtration compartments

2.1. Types of micro-organisms

The use of biofiltration processes to treat hydrophobic compounds face problems, due to their low solubility in water [7]. Absorption rate of compounds such as alkanes, alkenes, and aromatics into bacterial biofilm is not high [8,9]. During this time, efficiency of bio-filters decreases because of acidification and drying. To overcome these problems, bio-filters with fungal bio-films have been developed, whereas bacteria are less resistant to low pH or dry environment than fungi [11]. This property of fungi is useful for the treatment of acidic gases in dry condition. Fungi can take up hydrophobic compounds directly [11]. Due to the absence of water layer between fungi biofilm and gas phase, hydrophobic compounds gets removed faster than with bacterial biofilm [12].

Fungi like bacteria needs nutrient to grow [13]. A large-scale pilot of fungal biofiltration process has been made to remove polluted air with ethane, ethyl benzene, hexane, toluene, alpha-pinene, 1,3-butadiene, and xylene [1, 14]. In the above studies, the effect of humidity and pH on biodegradation rate was demonstrated. The BF processes were tested for pH between 4 and 8. For different pH value, the RE of biofiltration process was different. Biofiltration processes were able to remove pollutants in lower pH better than higher pH. Fungi and bacteria were developed during the operation of bio-filter in low and high pH. In order to stimulate drying, injection of water was stopped. Biofiltration process that was operated in low pH (equal to 4), could remove more than 125 g/m^3 of pollutants up to 1,000 h. However, the same biofiltration process in high pH, could remove only 20 g/m^3 of pollutants during the same period. Fungal biofiltration process was able to remove 99% of pollutants at optimum conditions. Higher growth rate of fungi can clog the biofiltration processes in the reactor bed. To solve this problem the use of mites as predators were identified [13]. According to Groenestijn and Kraakman, emission of spores from fungal bio-filters is not effective on human and animal health [5]. According to Sperka and Kennes, many types of fungi are capable of growing in bio-filters [15, 16]. Using fungi in bio-filters can increase the elimination capacity of pollutants up to 10 times more than bacterial bio-filter [13]. Although a number of pilot project using fungal biofiltration process have been carried out, but the application of a larger scale of fungal biofiltration process reactor has yet to be installed commercially. A simple protocol to choose biological type filtration is shown in Fig. 2.

2.2. Development of attached and suspended micro-organisms

Biological air pollution control technologies such as BFs, bioscrubbers (BSs), biotrickling filter reactors (BTFRs), and suspended growth reactors (SGRs) can

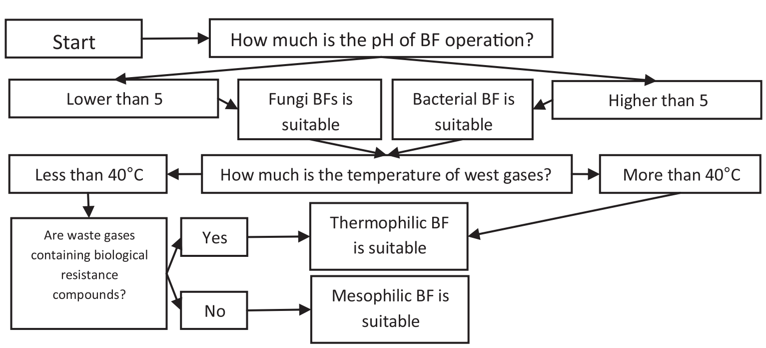

Fig. 2. Standard protocol to choose suitable biological type filtration.

be cost-effective alternatives to treat polluted gas [17]. Fig. 3 presents these four methods schematically.

The most popular gas-phase treatment technologies are BFs, BTFRs, and SGRs. The difference between a BF and BTFR is that BF is packed with some natural maters like compost, soil or sludge. These natural materials contain different strains of micro-organisms. BTFRs are packed with natural or synthetic matters that do not have indigenous micro flora such as lava rock or ceramic particles. For this reason, BTFRs need micro-organisms for inoculation. BF and BTFR remove pollutants from polluted air that are passed through a bed of biologically active solids (Fig. 3(a)). Soluble chemicals transfer from the gas phase into the water surrounding the media, where attached microbes degrade the organic chemicals in the liquid biofilm (Fig. 4). The biofilm thickness ranges from 10 to 10,000 mm. However, an average of 1,000 mm or even less is obtained. The activity is raised up to the level called active thicknesses. Above this level, diffusion of nutrients becomes a limiting factor thus differentiating an active biofilm from an inactive biofilm [18].

The operations of BFs or BTFRs consist of various phases (1) transfer of the pollutant air into the aqueous phase (2) adsorption of pollutants onto the medium or absorption into the biofilm; and (3) biodegradation of pollutants within the biofilm. The steps are shown in Fig. 4.

Homogenous distribution of inlet gases is very important in achieving higher removal rate in BFs or BTFRs. Distributions of inlet gases into reactors can be monitored by smoke or trace gases and by infrared method for detecting all parts of the reactor [19–21].

An SGR removes pollutants using biologically treating polluted air bubbled through an aqueous suspension of active micro-organisms (Fig. 3(c)).The performance of SGR relies on the mass transfer of organic chemicals and oxygen from the gas to liquid phase, where the suspended active micro-organisms biodegrade the contaminant of interest. It can be seen from Fig. 3(d) that the bioscrubber is being divided into two separated parts (a) scrubber that can provide a wide area to transfer pollutants from gas phase to a liquid solvent, (b) Suitable treatment facilities to remove pollutants from liquid solvent. Using a bioscrubber, pollutant can be transferred from gas phase to a liquid solvent which is commonly water. Liquid solvent containing pollutants is transferred to a suitable treatment facility to remove pollutants and it can be recycled again after treatment. If liquid solvent is water, activated sludge or biological trickling reactors can be used to remove pollutants.

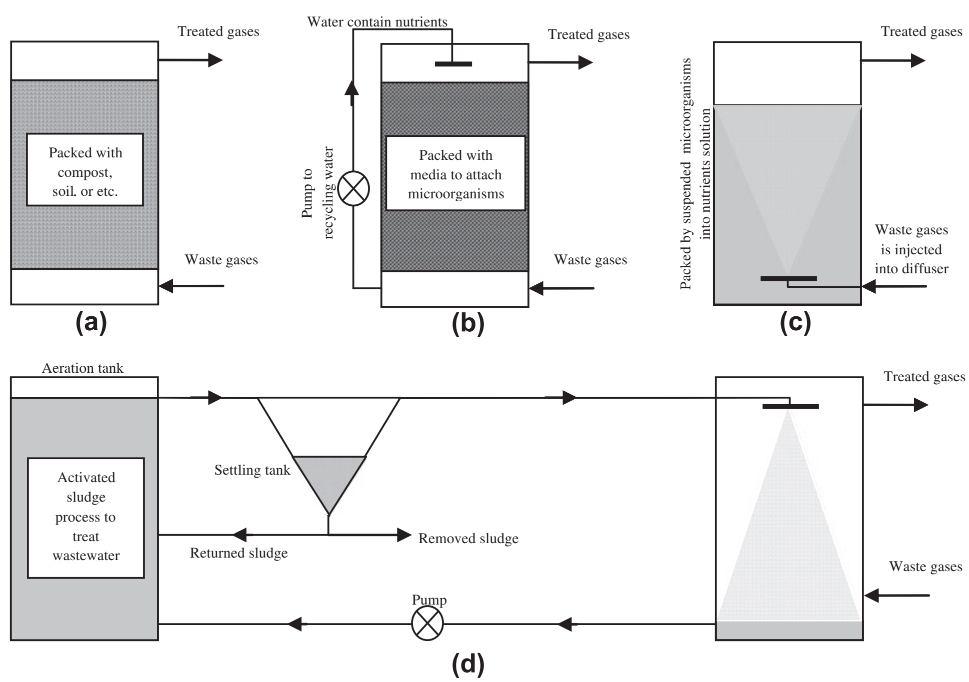

Fig. 3. Different methods of biological air treatment: (a) BF, (b) biotrickling filter, (c) suspended growth reactor, and (d) bioscrubber.

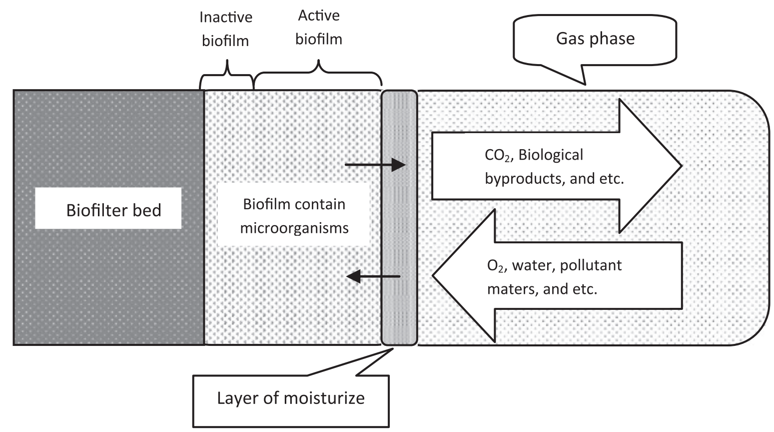

Fig. 4. Schematics of biofilm into a BF or BTFR.

A major difference between these processes is that pollutants degradation in a BF relies on attached micro-organisms whereas, in a SGR, suspended micro-organisms in an agitated mixture cause such degradation. Under properly managed conditions, bio-filters are effective in the treatment of pollutant removal. Although previous researches on BF has shown that it faces some problems, such as plugging from excessive biomass growth and drying of the bio-filter medium, but it can be as efficient as SGR [18, 22]. SGR has advantages which include absence of plugging and easier biomass and nutrient control, but has other operational concerns [23, 24].

Aaron et al. performed research on BF and SGR [17] for comparing the performance of a typical compost BF to a SGR for the removal of polluted air contaminated with toluene. The results indicated that SGRs could effectively treat gases containing toluene. For mass loadings ranging from 5 to 30 mg/l–h, the BF, and SGRs achieved similar toluene removals in the range of 96–99.7%. Drying of the BF medium occurred at high mass loadings, which were considered as a problem. Based on the above discussion some advantages and disadvantages of different methods of biofiltration process are summarized in Table 1.

2.3. Supporting materials

Biological reactors are increasingly becoming popular process, in which solid media is added to reactors in order to provide attachment surfaces for bio-films, thereby increasing microbial concentrations and rates of contaminant degradation [25]. Packing materials are critical segments of biofiltration process. These materials provide most important motivation for microbial growth. According to Kumar et al. following characteristics are noticeably required for an ideal biofiltration processes bed: high porosity, optimum specific surface area, high-quality water retention capacity, manifestation and availability of intrinsic nutrients, presence of dense and diverse indigenous micro flora [18].

The most frequently used supplies in biofiltration process beds are: (1) compost, (2) coconut fiber, (3) soil, (4) peat, (5) lava rock, (6) activated carbon, (7) synthetic materials, and (8) ceramic among these compost, coconut fiber, soil, and peat are commonly used in BFs. These materials are generally abundant and economical as well as lava rock, activated carbon, synthetic materials, and ceramic are usually applied in BTFRs.

Supporting materials that can be used during biofiltration of polluted gases are divided into two important categories namely organic and inorganic materials. Organic materials including composts and sludge have been used in many studies [26]. The main advantages of using organic materials are that they are easily available. They also contain the necessary natural micro-organisms, which exclude the necessity of inoculation [27]. These materials contain nutrients (for e.g. phosphorus, nitrogen, etc.), which are necessary for the growth of micro-organisms. The inorganic materials have been applied to treat polluted air. Till date, less organic materials are used because they cannot be used as unaided.

Due to significant presence of nutrients in compost and being less expensive, it is the most common material used in biofiltration process [28]. The experiments conducted on BFs packed by compost shows that it has tremendous limitations during long-term experiments. The lifetime of compost as a BF packing material is generally less than six months. Based on previous studies, the suspected reasons are compaction of the compost into BF and depletion of

Table 1
Advantages and disadvantages of using different type of biofiltration processes

Reactor type	Advantages	Disadvantages
BFs	Inexpensive method	Short durability of natural matters as biofilter bed in comparison to synthetic matters
	Simple operation	Problems in treating acidic gases
	Using natural matters as biofilter bed	BFs faces other problems such as: plugging, drying compaction of natural bed and channeling
	Does not need inoculation	High-pressure drops
	Nutrients need not be provided	
	Can remove all types of pollutants	
	Does not produce waste	
BTFRs	High efficiency	Needs preparation of water and nutrients
	Does not produce wastewater	Synthetic supporting materials are expensive
	High durability of synthetic beds	Complex operation
		Very expensive
BSs	Hot polluted air is treatable	Produces wastewater
	Does not face plugging	Expensive
	Does not face drying	Complex operation
SGRs	Biomass and nutrient control is easier	Not efficient for insoluble pollutants removal present in water
		Complex operation
	Does not product untreated wastewater	High-pressure drops
		Faces problems like: plugging and drying

its nutrient contents with respect to time [29]. Compaction of compost in BFs is also the reason for more pressure drop and the apparition of critical issues in the BFs. Compost has also some serious problems associated with treating acidic gases, packing, replacing, and drying. Nowadays, the use of compost is more popular than using lava rock or synthetic packing in biofiltration process.

Lava rock is another packing material that is being used in biofiltration processes. The lifetime of lava rock is more than 10 years. Because the flow of nutrients solution, the moisture is not a problem to BTFRs packed with synthetic packing or lava rock. For this reason, operations of BTFRs packed with lava rock or synthetic packing are easier as compared to BFs packed with compost. In recent years, many BTFRs packed with synthetic materials have been installed with great success [30].

Soil and peat are other types of materials used frequently as BF's bed. Although soil has various micro-organisms, but it has some important problems, such as nutrients limitation, low specific area, and spawn high-pressure drops [31]. The main advantages of using peat as BF's bed are that it has high water-absorbing capacity, high specific area, and high porosity. It does not have intrinsic nutrients and indigenous microflora. In some studies, a mixture of organic and inorganic materials was used. This mixture was used to improve the mechanical characteristics of BFs, which in turn declines the risks of compaction, while channeling the problems during biofiltration of polluted air [32]. Physical properties of organic materials like porosity, specific surface area, etc. can also be more easily adjusted by adding appropriate amounts of inorganic materials. To improve physical and mechanical properties of BFs, several natural or manufactured materials, such as rocks, ceramics, glass, plastics, and many other materials can be mixed together with organic substances. Although the use of organic and inorganic materials mixture has some advantages, inorganic materials generally do not contain any nutrient when they have high densities [5].

A comparison study between a BF packed by organic material and a BTFR packed with inorganic materials to treat air contaminated with methane has been carried out by Mohammad et al. [33]. Their study showed that BTFR packed with inorganic materials can give elimination capacities two-times higher than BF with the organic materials.

Activated carbon is another useful packing material. According to some reports, pollutants RE in biofiltration process is increased by the use of granular activated carbon as supporting material [34]. In this condition, the BF need not renew or exchange granules because micro-organisms can remove absorbed pollutants from activated carbon [34]. This type of BFs has resistance against shock loading. Shorter BFs bed length is another advantage of using activated carbon as supporting material. Due to these advantages the use of combination of BFs and activated carbon is increasing [35].

Based on previous studies, porous ceramic material is the most suitable support media for packing fungal biofiltration process. This type of packing media has also been successfully used for growing bacteria onto the BTFRs [36]. The disadvantage is that ceramic particles have more weight.

2.4. Effect of temperature on biofiltration processes

Based on several reports, the temperature is one of the crucial parameters playing a major role in biofiltration processes efficiency. In most laboratory studies or industrial applications, the BF unit was run under normal temperature between 15 and 30˚C [37]. However, industrial polluted air has temperatures more than 30˚C, then the polluted air needs to be cooled before processing to the biological treatment. The biofiltration process is divided into mesophilic and thermophilic based on temperature requirement. A mesophilic reactor contains organisms that can grow best in moderate temperature typically between 20 and 45˚C. On the other hand, a thermophilic reactor contains an organism that flourishes in high temperatures between 45 and 122˚C. The thermophilic micro-organisms are found in different geological formation on the earth including the hot springs and deep-sea hydrothermal vents, as well as decaying plant matter, such as peat bogs and compost. Many researchers could isolate several thermophilic micro-organisms from these places and use them for biofiltration processes. Some laboratory studies were performed by these micro-organisms on the bio-filtration of polluted air at a temperature more than 50˚C [38]. To use thermophilic biofiltration processes, thermo-stable packing is needed. Using thermophilic micro-organisms would offer great cost savings and extend the applicability of BFs. Only few studies can be found on the thermophilic treatment of polluted air [39].

The Arrhenius equation can be used to model the effect of temperature in gas-phase of bioreactors [40]. Although some authors observed a decrease in performance when switching from mesophilic to thermophilic conditions [41, 42], several other biofiltration studies demonstrated higher removal rates in thermophilic BFs in comparison to mesophilic ones. For example, Deshusses et al. [43] observed that removal of ethyl acetate in a thermophilic BF was more than the mesophilic one. Luvsanjamba et al. [44] could find the same results in thermophilic (52˚C) and mesophilic (25°C) biotrickling filters treating mixtures of iso-butyraldehyde and 2-pentanone. The thermophilic one could reach higher elimination capacities. In addition, Matteau and Ramsay [45] could achieve higher removal rate to remove toluene from air using a BF packed by an active compost of maple leaves and alfalfa as support materials. Like mesophilic BFs, approximately all of VOCs are removable by thermophilic BF [46]. The first full-scale thermophilic BF was installed in 1997. This BF (60˚C) was used for removal of odor at a cocoa factory. The biofilter was successful in removing 97% odor [5]. Due to the success of the first thermophilic BF, a new one was made in 1999 at another cocoa factory. A bio-scrubber (65˚C) was made for treating polluted air contaminated with formaldehyde at a wood particle board factory [15] and the bio-scrubber has successfully worked until 2005 [5].

2.5. Effect of pH on biofiltration processes

Previous studies have proven that pH can influence biofiltration processes efficiency significantly. Microbial activities can be severely disturbed by conduction of biofiltration processes on the sub-optimum pH range. Based on Lu et al.'s study, maximum degradation rate of air contaminated with benzene, toluene, ethyl benzene, and xylenes using a BF was observed during BF experiment between pH values of 7.5 and 8.0 [35]. Effect of pH (between pH 3.5 and 7.0) on biodegradation of air contaminated with alkyl benzene was also evaluated by Veiga et al. [47]. They could show that alkyl benzene degradation increased with pH.

2.6. Prevention of biomass clogging by mechanical force

Preventing bio-trickling filter clogging by micro-organisms is a problem for using this system on large scale. The use of high salt concentrations, limitation in potassium and phosphorus and predation by higher organisms, were some of the methods to prevent bio-trickling filter clogging [14, 48, 49]. The use of mechanical force to prevent micro-organism accumulation has been studied. As a result of these studies, moving bed reactors were developed. In the moving bed reactors, mechanical forces are used to remove extra biomass [50]. The moving bed reactors are a rotating cylindrical tower. Polluted air is ventilated continuously into the reactor. These types of bio-filters are packed with synthetic media, which are continually removed at reactor. Removed media is returned to the reactor after mechanical cleaning. Bio-trickling filters can be used for treatment of wastewater and polluted air in the same time. A full-scale bio-trickling filter has been installed for the treatment of air ventilation at a chicken slaughterhouse and wastewater. These bio-filters can treat 650 m^3/d wastewater and 30,000 m^3/d polluted air at the same time and the volume of the reactor was 150 m^3.

3. Overview of the biofiltration processes control techniques

3.1. Use of biofiltration processes to remove organic and inorganic gases

Wide range of industries uses VOCs. These industries eventually release a part of VOCs into the atmosphere. Controlling the toxicity of VOC is necessary to avoid widespread health problems [1]. Some VOCs are also considered as mutagen and carcinogen [47, 51]. Thus, it is important for human health and environmental quality to decrease the VOC emission. For these reasons some VOC removal methods have been developed, such as physical absorption, chemical reaction, and biological filters. However, the physical methods such as absorption on porous materials or chemical reaction may not completely remove organic matters such as VOCs from polluted air steam. Despite complexity of biological systems, they have high efficiency and low operational cost. For treating large flow rates of gas with relatively low concentrations of pollutants, biological systems are environmental-friendly technologies [16].

Biodegradability of several VOCs has been proven and because of this property, biotechnology process is very suitable for removal of VOCs from the polluted air [12]. Traditionally, BFs are used to treat effluents with VOC concentrations lower than 10 gm^{-3}. Several reported findings have shown that a number of gaseous pollutants contaminated with VOCs such as toluene, trimethylamine, dimethylamine, formaldehyde, and methanol could be successfully degraded in BFs [38, 53–55]. It has been reported that a large number of fungi and bacteria could grow on supporting materials into BFs that have been fed by air contaminated with VOCs [16, 56, 57]. In addition, some reported findings have shown that BFs are usable in a wide pH range if suitable micro-organism of mixed cultures is used [47]. Po¨land et al. proved that acidophilic bacteria have a low yield coefficient [58]. A similar characteristic is found in thermophilic micro-organisms [33]. Generally, generating less biomass is a good factor to allow pressure drop to be reduced in BFs. Ramirez et al. studied the kinetics of microbial growth, biodegradation of methanol, and toluene in BFs. Their BF removed the mixture of toluene and methanol at same time [55]. Prado et al. used three different inert filter bed materials (lava rock, perlite, activated carbon) for biodegradation of a mixture of formaldehyde and methanol [54]. In another study, Perado et al. also used a BTFR for biodegradation of polluted air containing formaldehyde, methanol, dimethylether, and carbon monoxide [51]. They could achieve 100% removal of pollutant air by a BTFR. A packed BTFR with ceramic particles and pure mi cro-organisms has been also used to remove trimethyl amine from waste gases [36].

3.2. Review of the application of biofiltration processes in removing certain gases

3.2.1. Removal of H_2S

Natural gas and biogas contain less amounts of H_2S. The main method to remove H_2S on large scale is using amine absorbers [5]. The reaction in this method is:

$$H_2S + OH^- \rightarrow HS^- + H_2O \tag{1}$$

To remove H_2S on small scale, a wet scrubber based on reaction between iron chelates and H_2S is usable. By combining wet scrubbers and biological systems, bio-scrubbers were developed. Bio-scrubbers can be used to remove H_2S from polluted gases. In this system, H_2S is dissolved in the water and eventually a biological system converts dissolved H_2S into elemental sulfur [59]. Biological systems can be used to remove H_2S emitted from anaerobic reactors. The bioreaction to convert H_2S into elemental sulfur is:

$$HS^- + \frac{1}{2}O_2 \rightarrow S_0 + OH^- \tag{2}$$

These systems are used when the sulfur-loading rate is under 15-ton sulfur/d [60, 61]. A bio-scrubber described by Dijkman was capable to treat 400 m^3 biogas/h. This bio-scrubber could remove 99% of H_2S from waste air. According to Dijkman, using bio-scrubber 90% of NaOH can be saved in comparison to conversional scrubbers [62].

Natural gas contains H_2S and it can be treated by similar methods. Some studies have been done to compare H_2S removal in bio-filters and conventional methods such as amine absorbers. These studies show that, to remove H_2S, biological method can be as good as conventional methods [60]. In some biological methods, H_2S of natural gas can be converted into elemental sulfur (S_0) at high pressure and can be reused in H_2SO_4 in factories [62]. In 2001, the first large-scale high-pressure BF to treat natural gas containing H_2S was installed in Canada. Outlet H_2S concentration in this BF was lower than 4 ppm [5]. Some micro-organisms such as *Thiobacillus* or autotrophic bacterial were active to remove of H_2S in biological systems.

3.2.2. Removal of SO_x

Other important pollutant which is removable with BFs is SO_x [63]. By conventional methods SO_x can be removed using dilute solutions of limestone or NaOH. High cost of chemicals and product of disodium sulfate are the disadvantages of this method [64]. SO_x are also removable using biological methods [61, 64]. A hybrid system can be used to remove SO_x. In the first stage, SO_x is absorbed by a scrubber [5]. The reactions in this stage are:

$$SO_2 + NaHCO_3 \rightarrow NaHSO_3 + CO_2 \quad (3)$$

$$NaHSO_3 + \frac{1}{2}O_2 + NaOH \rightarrow Na_2SO_4 + H_2O \quad (4)$$

The liquid is transferred to anaerobic bioreactor. In this reactor, the sulfates and sulfites are reconverted to sulfide by micro-organisms. Micro-organisms in this system need an electron donor. Hydrogen, methanol, and ethanol have been used as electron donors. The following bio-reaction would happen in this stage [5]:

$$NaHSO_3 + 3H_2 \rightarrow NaHS + 3H_2O \quad (5)$$

$$Na_2SO_4 + 4H_2 + CO_2 \rightarrow NaHS + NaHCO_3 + 3H_2O \quad (6)$$

This system can remove 99% of SO_x from inlet gases with loading rate equal to six kilogram SO_2/hour [61].

3.2.3. Removal of NO_x

NOx emission into atmosphere can be a reason of many environmental problems such as acid rains. Many physical and chemical methods have been developed to treat air contaminated with NOx. Cetinkaya et al. (2005) performed a study on the NO_x removal using bio-scrubber that shows which, NO_x biological removal is difficult because, more than 90% of NO_x is NO and this compound has a poor solubility in water, Fe(II)EDTA can be used to overcome this problem. Because NO can react with Fe(II)EDTA easily based on following reaction [64].

$$\mathrm{Fe(III)EDTA_{aq} + NO_{aq} \rightarrow Fe(II)EDTA - NO_{(aq)}} \quad (7)$$

The consequence of the reaction between NO and Fe(II)EDTA is $Fe(II)[EDTA]NO_2$. Using this method NO can be absorbed into scrubber liquid. Loading rate of NO and temperature are not important in this reaction. To treat the scrubber liquid containing $Fe(II)[EDTA]NO_2$ and NO_2, it is transferred to a biological anaerobic reactor. Eventually, $Fe(II)[EDTA]NO_2$ is converted to Fe(II)EDTA and nitrogen gas (N_2) by micro-organisms (based on following reactions):

$$24Fe(III)EDTA + C_6H_{12}O_6 + 24OH^- \xrightarrow{Microorganisms} 24Fe(II)EDTA + 18H_2O + 6CO_2 \quad (8)$$

$$12Fe(II)EDTA - NO + C_6H_{12}O_6 \xrightarrow{Microorganisms} 12Fe(II)EDTA + 6H_2O + 6CO_2 + 6N_2 \quad (9)$$

Scrubber liquid after treating can be reused. NO_x RE in this method is more than 80%. SO_x and NO_x can be removed at the same time by combining both of the denitrification process, which can also be applied as a promising alternative to remove NO_X. Denitrification is a chain of biological reaction to convert NO_x–N_2 [65].

$$NO_3^- \xrightarrow{Microorganisms} NO_2^- \xrightarrow{Microorganisms} NO + N_2O \rightarrow N_2 \uparrow \quad (10)$$

The complete denitrification process is presented:

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \quad (11)$$

The reactions mentioned above are anaerobic. Therefore, oxygen can act as an inhibitor. Mostly air contaminated with NO_x is a mixture of different gases with oxygen. Therefore, treatment of air contaminated with NO_x by biofiltration technologies is not simple. Jiang et al. [65] has shown that NOx removal in presence of oxygen (with oxygen concentration between 0 and 20%) is possible. However, high concentration of oxygen has a negative impact on NO_x removal.

3.2.4. Removal of CS_2

Some studies have been carried out to develop biological methods for removing of CS_2 from polluted air steam. In one of them, bio-filter was packed with a synthetic medium. After developing bio-films, CS_2

was injected to the bio-filter and was converted to water and sulfuric acid by micro-organisms. This bio-filter was conducted in pH less than 1. Bio-films in this study were full of acidophilic bacteria. A large-scale bio-filter was installed in a sponge factory to remove CS_2. Inlet gases were containing 300 ppm of CS_2 and 250 ppm H_2S with flow rate 50,000 m^3/h. The bio-filter can remove 90% of CS_2 and 95% of H_2S [46].

CS_2 is classified as hazardous matter in the USA. CS_2 is emitted into atmosphere from both natural and anthropological resources [66]. The most important anthropological resources of CS_2 are industries related to cellophane, rayon, and cellulose sponges production. Most of the time exhausted air from these industries is a mixture of CS_2 and H_2S. CS_2 concentrations in this exhausted air can be reached up to 4.7 g/m^3. Nowadays, many methods have been developed to remove CS_2, such as absorption, adsorption, thermal or catalytic oxidation, and biological methods. Different micro-organisms have been applied in biological methods to remove CS_2 from polluted air, such as photosynthetic, chemoautotrophic and heterotrophic bacteria, and even molds. Smith and Kelly [66] reported that among Thiobacillis strains, only Thiobacillus thioparus has the ability of CS_2 removal. CS_2 can be converted by micro-organisms to water and sulfuric acid.

$$CS_2 \xrightarrow{Microorganisms} H_2SO_4 + H_2O \tag{12}$$

A large-scale bio-filter was installed in a sponge factory to remove CS_2. Inlet gases were containing 300 ppm of CS_2 and 250 ppm H_2S with flow rate 50,000 m^3/h. The BF can remove 90% of CS_2 and 95% of H_2S from polluted air [46].

3.2.5. Removal of odor and NH_3

NH_3 can be an important contributor to the acid rain (EMEP, 2004). Pig stables are the important source of NH_3. Treatment is required because of the presence of some harmful matter in ventilation, such as ammonia and odor from pig stables. The treatment of pig stable's air is difficult, because the volume of air is high but concentration of pollutants is very low [53]. Scientists have developed some treatment systems such as bio-filters or bio-scrubbers to treat pig stable's air. Unfortunately, these systems are not efficient. Amongst the treatment systems to clean air, bio-trickling systems are more efficient and reliable. Some large-scale bio-trickling filter was installed to treat ventilation air from pig stables. Moussavi et al. developed a bio-trickling filter to remove pollutants from synthetic air contaminated with ammonia. Ammonia can be converted biologically to nitrate by nitrification process [53]. Some studies show that biological systems are capable of converting nitrate to nitrogen gas by denitrification process [1].

To prevent odor emission from the wastewater treatment facilities, covered tanks are used. The tanks containing crude wastewater are aerated and waste gases from this part have foul smell. After that the effluent gases are treated by various methods. Biological methods are very popular to remove odor. According to Groenestijn and Kraakman report, nearly 90% of the wastewater treatment plants in Netherland use gas treatment systems, 78% of them are biological systems and 23% use other systems such as chemical scrubbers or activated carbon [5]. In most European countries, installation of gas treatment systems has become obligatory for wastewater treatment plants.

3.2.6. Removal of alkanes

Because of low solubility of alkanes in water, biological treatment of alkanes faces many problems. Due to poor transferring of alkanes from gas phase to the aqueous phase, removal capacity is not high. To overcome this problem, non-biodegradable organic solvent is used in bio-trickling filter. In this bio-filter, a mixture of water and non-biodegradable organic solvent is continuously trickled on the bed, while polluted air is injected into the bio-filter [67]. The alkanes are solved in the organic solvent. After that micro-organisms have enough time to absorb and degrade alkanes. Groenestijn and Lake's [67] study indicated that 90% pollutants are removable by this process. This process could be an environmental friendly and cost-effective model to remove gases contaminated with alkanes. This process is applicable to treat both high and low solubility materials in the polluted gases.

3.2.7. Removal of Formaldehyde

Formaldehyde vapor is a waste gas that is released in the air worldwide from chipboard production, burning processes, synthesis of resin production, and chemical factories. Some researchers estimate a global emission of 20 million tons of formaldehyde in year that it keeps going on year-by-year [5]. Because of the high toxicity of formaldehyde for micro-organisms, its biological treatment faces many problems [68]. Some pilot studies have been performed on biodegradation of formaldehyde in air. For example, Prado et al. used three different inert filter bed materials (lava rock, perlite, activated carbon) for biodegradation of a mixture of formaldehyde and methanol [54]. A bio-trickling filter was used and the results have shown that formaldehyde can be removed completely from air. In another study, Perado et al. used a bio-trickling filter for biodegradation of polluted air containing formaldehyde, methanol, dimethylether, and carbon monoxide [51]. They could achieve up to 100% removal of pollutant air by a bio-trickling filter. The results of this study have shown that formaldehyde is biodegradable in air contaminated with different type of pollutants (organic and inorganic). For achieving better results, the use of long-term micro-organism adaptation is important. Formaldehyde with aerobic and anaerobic condition can be removed by micro-organisms. Different pathways have been proposed to explain the anaerobic biodegradation of formaldehyde according to the intermediate products observed. For example, based on González et al. [69], formaldehyde is biologically converted into formic acid and methanol. Then formic acid and methanol are converted to methane and carbon dioxide by micro-organisms. These reactions are shown in the following equations:

$$HCHO + H_2O \rightarrow H_2 + HCOOH \tag{13}$$

$$HCHO + H_2 \rightarrow CH_3OH \tag{14}$$

Another pathway was proposed by Oliveira et al. [70]. Based on their pathway, formaldehyde are firstly converted to volatile fatty acids, especially formic acid. These acids can be secondly converted to acetic acid. Finally, acetic acid is biologically converted to methane and carbon dioxide under anaerobic condition [70]. Aerobic formaldehyde removal can be accrued by two possible pathways that they show in the following equations:

$$2HCHO \xrightarrow[\text{dismutase}]{\text{Formaldehyde}} CH_3OH + HCOOH \tag{15}$$

$$HCHO \xrightarrow[\text{dehydrogenase}]{\text{Formaldehyde}} HCOOH \tag{16}$$

First pathway to aerobic formaldehyde removal is based on converting formaldehyde to methane and formic acid by formaldehyde dismutase mechanism. This pathway is accrued if the micro-organism has a formaldehyde dismutase enzyme. Second pathway is based on converting formaldehyde to formic acid by formaldehyde dehydrogenase mechanism. This pathway is accrued if the micro-organism has the enzymes formaldehyde and formate dehydrogenase [71].

3.2.8. Removal of CH_4

Methane has been ranked number two among important greenhouse gases [13]. Its worldwide contribution to the greenhouse effect is estimated to be 15%. Methane has a long lifespan in the atmosphere of around 12 years [72]. Methane emissions are released by oil and gas industries, from landfills, and from agriculture. Anthropogenic sources are the most important part of the total worldwide emissions of methane [73]. Biofiltration can be used to treat air contaminated with methane. Few reports have been published on treatment of air contaminated with CH_4 using biological methods. One of the first reports about CH_4 biodegradation was carried out by [74]. In this study, glass tubes 10 mm long and with an 8 mm diameter were applied as supporting media in a bio-trickling filter reactor for biodegradation of CH_4. Ninety percent of CH_4 removal was achieved when the hydraulic retention time and inlet concentration was 20 min and approximately between 1.6 and 6.5 g/m^3, respectively.

An open BF packed by crushed porous clay was applied to remove methane emitted from a landfill site. During this study, the methane-loading rate was from 0 to 247 g/m^3/h based on the natural cycle of methane emissions within the landfill. This BF could achieve elimination capacities up to 80 g-CH_4/m^3/h [75]. Their study elaborated that the inorganic material can give elimination capacities two times higher than those with the organic material. Although several studies have been reported on the influence of the hydraulic retention time and of the interruption of the irrigation for BF treating several pollutants [52], but to our knowledge, only the work reported by Nikiema and Heitz [76] was directly related to methane biofiltration.

4. BF design

Nowadays, biofiltration technology has been increasingly applied for the treatment of air contaminated with organic and inorganic pollutants. Biofiltration can be used to treat insoluble and recalcitrant compounds, if it is properly designed [77, 78]. Due to the homogeneity of the packing material and complexity of the physical, chemical, and microbiological phenomena involving in the biofiltration process, the use of a unique equation to design is not possible. Consequently, failure of poorly designed BFs has occurred when a wrong equation was used. It can

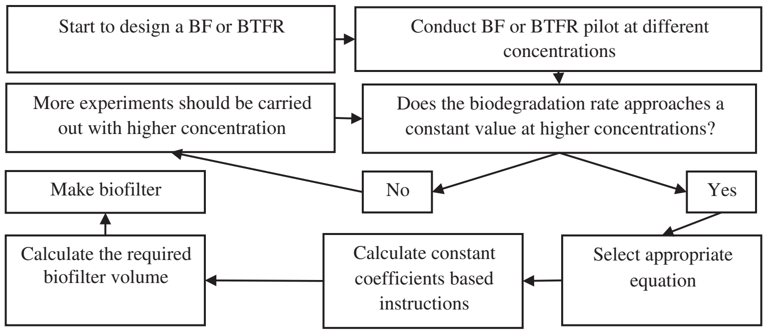

Fig. 5. A standard protocol to biological processes designing to treat polluted air.

cause some operators to prefer other treatment options. Several approaches about BF designing have been reported worldwide. Suggested models in previous studies are divided into two categories, micro-kinetic and macro-kinetic models. The following sections present an overview of some important macro-kinetic models. Biological treatment of polluted air is a complex process, which includes many physical, chemical, and biological phenomena [68]. It is commonly assumed that bio-films do not have any limitation for moisture, oxygen, and nutrient contents. The following equation has been suggested by Zamir et al. for BF designing [79]:

$$\frac{V}{(C_{in}-C_{out})Q}=\frac{K_m}{r_{max}}\times\frac{1}{C_g}+\frac{1}{r_{max}} \quad (1)$$

where r_{max} maximum elimination capacity (mg/L.min), C_g logarithmic average of inlet and outlet concentrations of pollutants in the gas phase (mg/L), K_m saturate constant (mg/L), C_{in} inlet concentration (mg/L), C_{out} outlet concentration (mg/L),V gas flow rate (L/min), and Q bio-filter volume (L). To calculate logarithmic average (C_g) Eq. (2) is used.

$$C_g=\frac{C_{in}-C_{out}}{ln(\frac{C_{in}}{C_{out}})} \quad (2)$$

By solving Eq. (1) to find V, Eq. (3) was calculated.

$$V=\frac{(C_{in}-C_{out})(K_m+C_g)Q}{r_{max}\times C_g} \quad (3)$$

As it can be seen, Eq. (1) is similar to $y=ax+b$,where a and b are slope and interception of curve y vs. x, respectively. In this equation, y is $1/C_g$ and x is $t/(C_{in}–C_{out})$. Also, a and b are K_m/r_{max} and $1/r_{max}$, respectively. By plotting $1/C_g$ vs. $t/(C_{in}–C_{out})$ constant coefficients r_{max} and K_m in Eq. (5) are calculated.

Another equation published by Streese et al. is [80]:

$$\frac{1}{r(c)}=\frac{1}{k_1}\times\frac{1}{c}+\frac{k_2}{k_1} \quad (4)$$

Eq. (4) is also similar to $y=ax+b$, where a and b are slope and interception of curve y vs. x, respectively. In this equation, y is $1/r(c)$ and x is $1/c$. Also, a and b are $1/k_1$ and k_2/k_1, respectively. By plotting $1/r(c)$ vs. $1/c$ constant coefficients k_1 and k_2 in Eq. (4) are calculated. After calculation of k_1 and k_2 using Eq. (5) volume of BF is calculated.

$$V=\frac{(ln\frac{C_{in}}{C_{out}})+k_2\times(C_{in}-C_{out})}{k_1}\times Q \quad (5)$$

where $r(c)$ degradation rate at concentration c (mg m^{-3} h^{-1}), k_1 kinetic constant (h^{-1}), k_2 kinetic constant (m^3 mg^{-1}), C_{in} inlet concentration (mg m^{-3}), C_{out} discharge concentration (mg m^{-3}), Q gas flow rate (m^3 h^{-1}), and V bio-filter volume (m^{-3}).

Kinetic constants in the above equations (k_1 and k_2 or r_{max} and K_m) can be determined by conduction of BF at different inlet concentration, including given range from the expected inlet concentration to the targeted discharge concentration. The detected degradation rates are plotted over a suitable logarithmic average of the inlet and outlet concentrations of pollutants in the gas phase (C_g) for the respective experiment. Logarithmic average is calculated using Eq. (2).

Another macro-kinetic model ($RE=1-e^{-kt}$) has been reported by Fulazzaky and Omar [81]. It describes relation between RE and gas retention time (t). In this equation, k is biochemical reaction rate coefficient (in mg/L.s). Strauss et al. [80] described the relationship between RE (μ) and retention time (t) according to ($\mu=a-ae^{-bt}$), where a and b are constant coefficients. Fulazzaky et al. [81] have suggested the following (Eq. (23)) model for removal of formaldehyde by BTFR.

$$E = k\ln(\theta) + b \tag{23}$$

where E is the pollutants RE (in %), k is biochemical reaction rate coefficient (in % s^{-1}), θ is the gas retention time (in s), and b is the initial removal rate constant, which depends on the amount of formaldehyde dissolved in the nutrient solution (in %).

Based on previous studies following standard protocol for designing of BFs to treat polluted air can be established:

First step: choice of one of the above approaches for designing.

Second step: conduct BF or BTFR experiments at different concentrations. The single experiments should not focus on degradation but rather to cover a limited concentration range for each setting. The total of the experiments must cover at least the whole concentration range (C_{in}–C_{out}) expected for the considered application.

Third step: the degradation rate (r) should be plotted vs. logarithmic average (C_g). The degradation rate and logarithmic average can be calculated by Eq. (24) and (2), respectively.

$$r = \frac{(C_{in} - C_{out}) \times Q}{V} \tag{24}$$

Fourth step: the status of the plot must be assessed. If the degradation rate approaches a constant value at higher concentrations, a shift from first to zero-order kinetics must be considered and this result is satisfactory for doing next step. If the plot is fitted by linear regression with high-correlation coefficient, first-order kinetics can be assumed. In this situation, more experiments should be carried out with higher concentration.

Fifth step: based on the approach that was selected in step one constant coefficients can be calculated. For example: when Eq. 1 has been chosen, constant coefficients r_{max} and K_m should be calculated by plotting $1/C_g$ vs. $t/(C_{in}–C_{out})$. When Eq. 4 has also been chosen, constant coefficients k_1 and k_2 should be calculated by plotting $1/r(c)$ vs. $1/c$.

Sixth step: Calculate the required BF volume.

These steps have been summarized in Fig. 5.

5. Challenges of handling polluted gases in future

In the near future, the world population will increase and it means more air pollution will be generated. The number of chemical materials used by industries is also increasing yearly. We will have serious problems in the future, if new technologies for treatment of air are not developed rapidly. It is worth mentioning that some of the new technologies such as spacecrafts will need less energy and efficient systems for air recycling. During long-term space missions, preparation of fresh air is vital and BFs can be a useful system to achieve this objective. Biological air treatment system for spacecrafts can be an excellent choice. A combination of biological technology and membrane filtration has been developed to treat gaseous pollutants in aircrafts. In this system polluted air is transferred to a mass of micro-organisms on the other side of the membrane. This hybrid system could permit cabin air to be treated without producing much waste as well as active carbon. Promising experiments have already been performed by the European Space Agency in space station MIR and in the space shuttle Columbia (which disintegrated in the upper atmosphere during re-entry) [5].

6. Conclusion

This paper summarizes existing research in the area of biofiltration processes. At the end of this review, following can be concluded:

Based on previous studies biofiltration processes is divided into four categories containing chemical, physical, biological, and biochemical methods. Nowadays, the use of biological methods or biofiltration processes, such as bio-trickling filter and BFs have gained more interest among the scientists. All types of organic and inorganic pollutants can be removed using biofiltration process. Due to the several effective parameters of biofiltration processes operation used in system being complex, some of the comprehensive factors, such as pH, temperature or hydraulic retention time have a great effect on biofiltration processes efficiency. This paper further proposes a simple protocol to choose a suitable type of biofiltration process. In addition, a protocol to design biofiltration processes presented at this review is also considered very useful to have correct reactor volume. Gas retention time is the most important factor to control pollutants removal by biofiltration processes, which directly depends on reactor volume. By considering biological approach as an idealistic process, it is expected that air pollution problems can be controlled significantly when compared to physical and chemical approaches being used for treating polluted air.

Acknowledgements

The authors gratefully acknowledge financial support from UTM-GUP Grant (Vot. 03H92).

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