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Landfarming operation of oily sludge in arid region—human health risk assessment

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Abstract

Landfarming is becoming one of the most preferred treatment technologies for oily sludge disposal in the Arabian Gulf region in general, and in the Kingdom of Saudi Arabia in particular. This technology is considered to be, economical, energy efficient, and environmentally friendly with minimal residue disposal problems. Application of this technology in the region is simply based on the studies conducted in the United States of America and Europe. There have hardly been any scientific studies conducted to evaluate performance of landfarming technology under arid conditions.

Recently, detailed field experimental study has been conducted to evaluate the degradation process and health risk issues in landfarming under arid conditions. The study observed volatilization as the main process of hydrocarbon degradation, which can cause significantly high concentration of airborne volatile organic compounds (VOCs) in the atmosphere leading to serious human health risk to the onsite workers. It is particularly true in the early phase of the landfarming process (first 2 months from initial loading). This paper elaborates these findings in detail.

Keywords: Bioremediation; Landfarming; Arid region; Natural attenuation

1. Introduction

Landfarming also known as land treatment is a treatment technology that involves the controlled application of a waste on the soil surface and the incorporation of that waste into the upper soil zone [1]. During 1970s, when environmental concerns associated with uncontrolled disposal became apparent, and environmental regulations were established and

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Nomenclature

ABS	absorption into the bloodstream, dimensionless
ASTM	American Society for Testing Materials
AT	averaging time (years)
BTEX	benzene, toluene, ethylbenzene, and xylene
BW	average body weight (kg)
C	exposed concentration (mg/m^3)
C_{soil}	concentration in soil (mg/m^3)
CR	contact rate (m^3 per day)
d	depth of the contaminant zone (cm)
D_{eff}	effective diffusivity (cm^2/s)
ED	exposure duration (year)
EF	frequency of exposure (days per year)
H	Henry's law constant (cm^3 water/cm^3 air)
k_s	soil water sorption coefficient (g water/g soil)
L	length of the experiment cell (cm)
RR	retention rate (dimensionless)
TPH	total petroleum hydrocarbon
U_{air}	wind velocity (cm/s)
VOC	volatile organic compound

Greek letters

δ_{air}	air mixing height (cm)
θ_{as}	air content in soil (cm^3 air/cm^3 soil)
θ_T	total porosity of the soil (dimensionless)
θ_{ws}	water content in soil (cm^3 water/cm^3 soil)
ρ_s	soil density (g/cm^3)
τ	averaging time for vapor flux (s)

applied in North America and Europe (aimed at minimizing the risk of air and groundwater contamination), landfarming gained popularity. It became one of the most practiced and reported disposal methods for oily wastes in Canada, the United States (US), the United Kingdom, Denmark, Finland, France, The Netherlands, Switzerland, and Sweden [2]. By 1979, landfarming was the second most important disposal method used on a total dry weight basis among Canadian refineries, with landfilling being the first method [2]. In the US, it became the most common method used by major oil companies to dispose of their generated oily sludge. In 1983, it was estimated that at least one-third of all US refineries operated full-scale or pilot-scale landfarms [1]. Landfarming gained popularity over incineration, landfilling, and deep well injection due to its following distinct merits [3,4]:

- low energy consumption,
- low risk of pollution of the surface and groundwater due to the immobility of hydrocarbons or metals through the soil,

- minimal impact on the environment (good site appearance, absence of odors, etc.),
- relatively low cost,
- compliance with sound industrial practices and/or government regulations,
- minimal residue disposal problems, and
- compatibility of the technique with the climate, location and type of sludge treated.

In 1984, this method lost its popularity when the United States Environmental Protection Agency (US EPA) issued the land disposal restriction (LDR) as part of the hazardous and solid waste amendments (HSWA) to the resource conservation and recovery act (RCRA). On 18 August 1992, US EPA published a final rule (57 FR 37194, 37252), establishing treatment standards under the land disposal restrictions program for various hazardous wastes that include hydrocarbons. This LDR, prohibited the land disposal of untreated hazardous waste. Landfarm operators had two options in order to operate their facilities: to treat their waste below the EPA specified contaminant levels (referred to as treatment standards), or to submit a petition demonstrating that there was no migration of hazardous constituents from the injection zone [5]. As a result, most of the traditional landfarms in North America were closed.

In 1994, remediation by natural attenuation (NA) of organic pollutants began to receive considerable attention. Natural attenuation is the reduction in mass, mobility, or toxicity of contaminants in soils, sediments, or groundwater by naturally occurring physical, chemical, or biological processes, such as biodegradation, dilution, dispersion, adsorption, volatilization, and chemical stabilization. Several environmental regulatory agencies in the US have dedicated significant resources to developing guidance on implementing risk-based corrective action (RBCA) and NA [6,7]. When examining the main processes under NA, it is clear that NA is similar to landfarming but it is being proposed as a remediation method rather than a disposal method. Landfarming appears to be returning as a major remediation technology. At the same time, ASTM, EPA, and other agency guidelines have been used to calculate and interpret risks associated with petroleum release sites. These same guidelines are applicable to landfarms.

2. Landfarming in arid region with specific reference to Saudi Arabia

Saudi Arabia has the largest oil reserves in the world and produces approximately 8 millions barrels of crude oil every day. With seven refineries, 22 bulk plants, several terminals and operating tank farms, oily sludge is one of the largest categories of generated industrial wastes. In a survey conducted by Saudi Aramco in 1994, it was found that the oil industry generated approximately 30,000 m^3 of oily sludge every year [8]. This study also found that the main source of the oily sludge was tank bottoms. Other sources included API separator bottoms, operating slops, oil spills, operating residues and other miscellaneous sources.

In Saudi Arabia, the first landfarm was constructed and operated in 1982. As of 2002, seven landfarms exist in Saudi Arabia with more under construction. Kuwait also used landfarming and other technologies to treat sites that were contaminated with oil as a result of the burning of Kuwait's oil wells during the Gulf War [9]. Most of these landfarms are developed based on the literature obtained from the US and Europe. Prior to the study conducted by Hejazi [10], no detailed scientific study was conducted in the Arabian Gulf region to study its advantages and limitations. In 1997, a Regional Refineries Waste Management Workshop took place in Abu Dhabi, the United Arab Emirates, to discuss the methods used for the disposal of refinery wastes. None of the papers presented at this workshop contained any scientific issues related to landfarming, even though this method was discussed in detail [11]. There are, however, several indications that other countries in the Gulf region are moving in the direction of utilizing landfarming technology as the main method for treating their oily sludges.

Considering these facts, a detailed field investigation on the landfarm treatment of oily sludge is undertaken by one of the authors [10]. The investigation was aimed to study detailed kinetics of the degradation processes involved in landfarming under arid conditions as well as human health risk posed during the operation of this landfarming. This paper aims to present finding of detailed risk study of the landfarming operation.

3. Human health risk in landfarming

The risk associated with a landfarm operation is mainly due to the release of hydrocarbon compounds as a result of applying the sludge to the soil and also during degradation of oily sludge. The people who are directly exposed to these hydrocarbons include those who bring and apply the sludge to the site, workers who operate landfarming equipment such as dozers, and those who routinely collect samples from the landfarms. In the recent study [10], it has been observed that volatilization is the main process of degradation in landfarming activities in dry arid region. This raises a concern because volatilized contaminants may cause severe health hazard to onsite and offsite receptors.

Oily sludge measured in terms of total petroleum hydrocarbon (TPH) consists of thousands of compounds of which about 250 have been identified to date [12]. To characterize risk for these 250 compounds individually in the oily sludge might be impossible. This has been realized by a group established in 1993 from more than 400 institutes, companies and agencies to address the large difference between cleanup requirements used by different hydrocarbon contaminated sites in the United States of America. The group, Total Petroleum Hydrocarbon Criteria Working Group, identified 13 TPH constituents to be used to assess non-cancer risk, and benzene and carcinogenic polycyclic aromatic hydrocarbons (PAH) to be used as an indicator to evaluate cancer risk [13]. In present case, benzene is used for carcinogenic risk, whereas toluene, ethylbenzene and xylene for non-carcinogenic risk.

4. Approaches to risk assessment

One of the objectives of the detailed experimental landfarming study in arid region was to assess the health risk to onsite workers associated with volatile organic compound (VOC) emissions resulting from a landfarm operation. To fulfill this objective, a detailed risk analysis was conducted using two approaches. In the first approach, values monitored from this study were used; and in the second, mathematically calculated values of contaminant concentration in the atmosphere were used. The complete procedure followed in conducting the risk assessment is presented in Fig. 1.

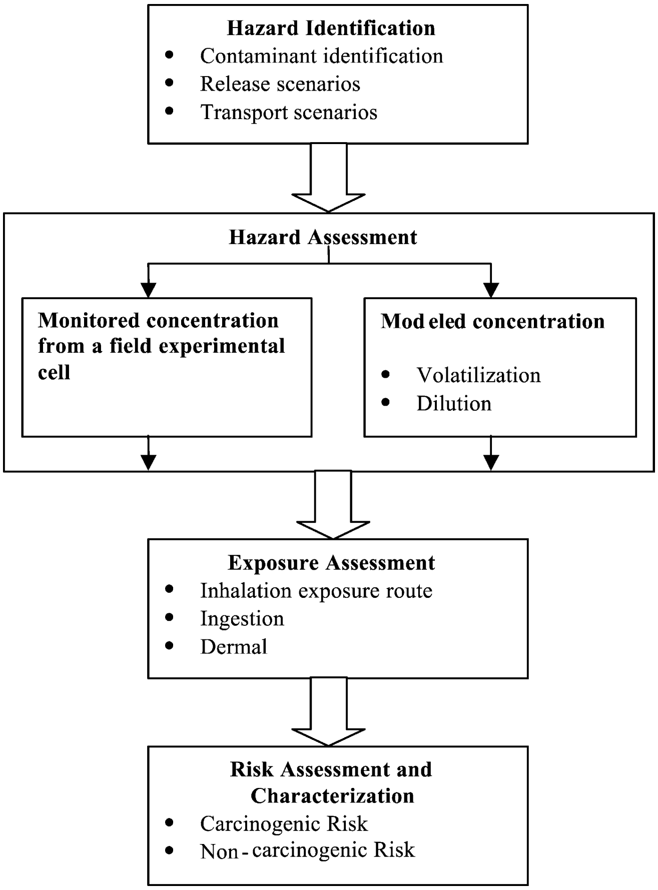

Fig. 1. Framework of the risk assessment used in the present study.

5. Hazard identification

A landfarm can pose many types of hazards to the environment, ecology, and human health through various exposure pathways.

- toxic organic compounds and or heavy metals may leach to the potable groundwater causing contamination, which on ingestion may cause health problems,
- heavy metals and/or organic compounds may migrate through the soil and contaminate other sites, and
- light volatile organic compounds may become airborne and come in contact with onsite and or offsite receptors through inhalation and ingestion and cause serious health problems.

Of the three possible scenarios mentioned above, scenarios 1 and 2 are not likely to occur at the studied site because

1. The groundwater at the present site is more than 6 m below ground surface, and it is unlikely that contaminants from a landfarm will leach to the groundwater [8,9]. The experimental investigation also shows no leaching of contaminants to the groundwater.
2. Although it is likely that residual organic compounds and heavy metals may migrate through the soil to other locations, the present site is in a remote area and any possible receptor is located more than 2 km from the site [9,10]. Therefore, this study does not include any risk assessment to offsite receptors.

The third scenario is the most likely scenario as a result of the high temperature and wind, and cause the volatilization of organic compounds. These compounds would be inhaled by onsite workers or transported to offsite receptors. The risk assessment reported in this paper covers the third scenario for onsite workers only.

The risk agents considered are benzene, toluene, ethylbenzene, and xylene (BTEX) because they are readily volatilized, persistent in nature, and are considerably toxic [14–17]. Benzene is a known carcinogen. As per the US Occupational Health and Safety Administration (OSHA), the allowable 8 h inhalation exposure limit of benzene is 1 ppm. Toluene is a suspected teratogen and its prolonged exposure may cause liver, kidney and brain damage. As per the OSHA regulations, 8 h work exposure limit of toluene should not exceed 200 ppm. Ethylbenzene is suspected to cause mutations and liver damage and its 8 h of work exposure limit is 100 ppm. A lengthy exposure to xylene may damage liver and kidney and can affect the normal function of the brain. The 8 h work exposure limit of xylenes is 100 ppm.

6. Hazard assessment

In present study two approaches have been used to conduct detailed hazard assessment.

1. Experimental approach: hazard assessment based on experimentally observed contaminant concentration.
2. Modeling approach: hazard assessment based on modeled contaminant concentration.

These two approaches are briefly discussed in the following sections.

6.1. Experimental approach at landfarming site

In this approach a full-scale field experiment that is most representative of field conditions under arid climate was conducted at Ju'aymah Oily Waste Landfarm, which is located in the Eastern Province of Saudi Arabia. This landfarm was constructed in 1994 and is located 20 km northwest of the Ras Tanura Refinery (the largest refinery in Saudi Arabia with a refining capacity of more than 350,000 barrels per day) and 2 km southwest of the Arabian Gulf. The test site is a low-profile sand dune field over a widespread marine sabkhah. Sediment deposits in the sabkhah include sand and clay. The top 1.2 m of the surface is mainly sand. Localized and shallow groundwater has some fresh or slightly brackish characteristics, as it is predominantly generated from rainfall that has been trapped (perched) in the shallow dune sediments. The depth of the groundwater at the site is approximately

6.6 m. Meteorological data collected near the site between 1964 and 1984 showed that the average annual rainfall in this area is approximately 3.4 in (85.6 mm) and the average annual evaporation is approximately 86 in (2190 mm), which clearly indicates that this area can be classified as an arid region.

6.1.1. Field cell design

A 2 m × 2 m covered cell were constructed in which nutrients were added in the mixed sludge. Air and water were also added on a weekly basis (Fig. 2). This cell was used to investigate (1) the effect of oxygen and water on the degradation process in a closed reactor (top covered with clay) and (2) to collect generated VOCs to assess the health risk to onsite workers. The design of this experiment cell is based on the design specified by Brown and Cartwright [18] and McNicoll and Baweja [19].

The fresh sludge used in this study was obtained from the bottom of a 1 million-barrel tank that contained Arab Medium crude. It was obtained during a scheduled maintenance, which is conducted once every 7–10 years. Arab Medium crude represents one of the largest categories of crude generated in Saudi Arabia. The mixed sand and sludge were placed inside the cell to a depth of 12 in (Fig. 2). The loading rate used in the cells was 150 g of sludge/kg of soil, which was based on the highest loading rate reported in the literature [20]. The selection of this high rate was based on the hot and arid climatic conditions in Saudi Arabia, which was expected to result in higher degradation due to speed up of bacterial metabolism (following Arrhenius law) and more volatilization. The weight ratio of sludge to sand in both the landfarm and bioreactor cells was approximately 1:7. The cell had 2340 kg of sand and 350 kg of sludge. The brand name fertilizer Phostrogen was used in this study with N:P:K ratio of 84:5.2:5.5. One kilogram of phostrogen was added to the cells to maintain a C:N ratio of 87:1. This is in line with the recommended ratio suggested by other investigators [21,22].

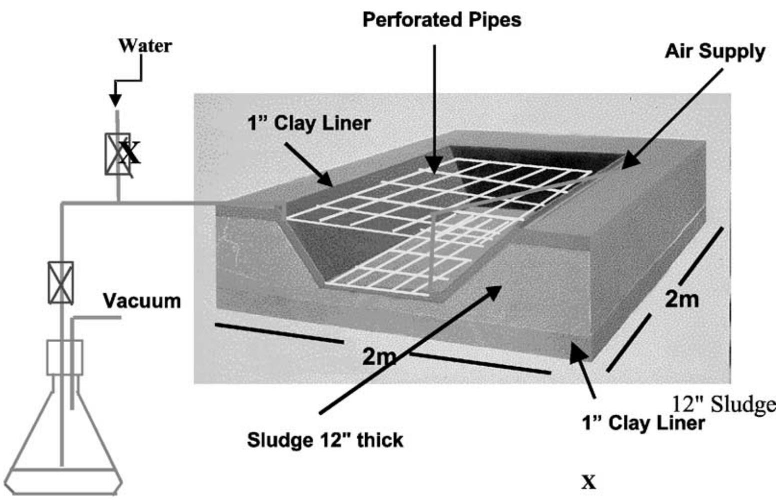

Fig. 2. Sketch of the experimental cell showing perforated pipes, liners, air, and water supply lines and vacuum connection for collecting VOCs.

The fertilizer (in powder form) was manually added to the sludge and was mixed with the sand without being dissolved in water. Following the placing of the sand and sludge mixture inside the cells, an apparent 1 in. thick layer of clay was placed on top of the cell. This layer was intended to act as an impermeable layer to minimize the loss of VOCs and to allow for the collection of VOCs (Fig. 2).

6.1.2. Field observations

Field experiment was conducted for 13 months from September 2000 to September 2001. For the period between 26 September and 24 October 2000, the sludge inside the landfarm cells was manually mixed every 2 weeks up to a depth of 10 in using shovels to maintain a homogeneous mixture. Between 4 October 2000 and 3 March 2001, tilling was applied and potable water and air were added to the landfarm and bioreactor cells once every 2 weeks. From 3 March 2001 until 4 September 2001, tilling, water and air were added once every week. The main reason for increasing the operating frequency was to keep the moisture content above 6% by weight. The quantity of water added to each cell was approximately 55 l each application time. The airflow rate to each bioreactor cell was 166 l/min. A total of 664 l of air was injected into each cell at each treatment cycle.

Samples were taken every month from the cells for VOC concentration estimation. The samples were collected using stainless steel air sampling canisters and analyzed for BTEX by EPA TO-14 method utilizing a GC–MS instrument. The results obtained are presented in Table 1.

6.1.3. Summarized results of the field study

The 13-month field study results showed that weathering (evaporation) and not biodegradation is the dominant degradation mechanism (loss) occurring in landfarms and bioreactors in the study area. Morgan and Watkinson [23] stated that the evaporation of crude oil in temperate climates is minimal and that in hotter climates, up to 40% of the crude may evaporate. The results of this study showed that up to 76% of the O&G in the sludge might degrade as a result of weathering.

Table 1
Observed and modeled contaminants concentration in mg/m^3

Compounds	26 September 2000	10 October 2000	26 November 2000	17 December 2000	3 February 2001	11 March 2001 & further
Observed concentration (mg/m^3)						
Benzene	0.265	0.003	<0.0006	<0.0006	0.0009	<0.0006
Toluene	0.711	0.007	<0.0007	<0.0007	0.0014	<0.0007
Ethylbenzene	0.165	0.001	<0.0008	<0.0008	0.0008	<0.0008
Xylene	0.571	0.005	<0.0008	<0.0008	0.0012	<0.0008
Modeled concentration (mg/m^3)						
Benzene	0.350	ND	ND	ND	ND	ND
Toluene	0.776	ND	ND	ND	ND	ND
Ethylbenzene	0.116	ND	ND	ND	ND	ND
Xylene	0.554	ND	ND	ND	ND	ND

ND: not detectable.

Among the three operating parameters (tilling, addition of water, and addition of nutrients), tilling was the main parameter responsible for achieving the highest rate of degradation (loss). The addition of nutrients and water resulted in slowing down the rate of degradation; this is mainly attributed to their effect on the soil properties and hence minimizing weathering. Nutrients are key parameters for promoting biodegradation. Only the cells where nutrients were applied showed evidence for biodegradation. This was clearly demonstrated by the C_{17}/Pr and C_{18}/Ph ratios obtained from the GC–FID analysis. Although biodegradation occurred at the cells that received nutrients, the extent of biodegradation was greater at those that had both water and tilling. However, the biodegradation was not extensive since the branched *n*-alkanes were intact.

The two-level factorial analysis (2^k) was used for the first time in a landfarming study to evaluate the differences in the performance of the tested cells. By using this method, the contribution of tilling, water, and nutrients was evaluated. The contribution of these operating parameters to the degradation process and the interaction between the parameters was also determined. This analysis clearly showed that the best response (reduction in O&G) is achieved when tilling alone is applied.

6.2. *Modeling approach*

This approach models release of contaminant through volatilization from the cell and subsequent dilution. The process of volatilization and dilution were calculated using ASTM's [6] proposed model (Eqs. (1) and (2)), which incorporate dilution using the Box model. Eqs. (1) and (2) are part of the ASTM proposed models for risk based corrective action guidelines [6]. These equations estimate the contaminant volatilization and their subsequent dilution. They were developed based on the conceptual model shown in Fig. 3. Eq. (1) is based on the partitioning of the contaminant from soil and water to the air and its subsequent dilution in the known volume of air (mixing zone). Eq. (2) is simple mass balance of the contaminant from soil and water to the mixing zone. As per ASTM guidelines, maximum of Eqs. (1) and (2) should be used for risk study. Details of these models are available in ASTM [6].

$$C = C_{\mathrm{soil}} \frac{2L\rho_{\mathrm{s}}}{U_{\mathrm{air}}\delta_{\mathrm{air}}} \sqrt{\frac{D_{\mathrm{eff}}H}{\pi\tau(\theta_{\mathrm{ws}} + k_{\mathrm{s}}\rho_{\mathrm{s}} + H\theta_{\mathrm{as}})}} \times 10^3 \tag{1}$$

$$C = C_{\mathrm{soil}} \frac{L\rho_{\mathrm{s}}d}{U_{\mathrm{air}}\delta_{\mathrm{air}}\tau} \times 10^3 \tag{2}$$

These equations were used for estimating contaminant concentration from experimental cells. Data used in the model are presented in Table 2, and the results obtained from both approaches are listed in Table 1. From these results it may be observed that the monitored values are comparable with the modeled concentrations; however, they are slightly lower than the modeled ones. This is believed to be mainly due to two reasons: (i) some of the volatile compounds were lost during the initial mixing, which was conducted away from the cell and this was not accounted for in the monitored value; (ii) although the used cell was covered with a clay liner, it is expected that some of the volatile compounds were lost through the cracks and other unavoidable openings without being accounted for in the monitored values. It was also observed from both the monitored and the modeled data that for the initial period (first 3 months) of the study, the concentrations of all four-reference compounds were quite high. These compounds included benzene, a known carcinogen.

7. Exposure assessment

Receptors, landfarm workers in the present case, would be exposed to airborne contaminants through various exposure routes: inhalation, direct ingestion, and absorption through the skin. A conceptual chart showing possible exposure scenarios is presented in Fig. 3. Among these possible exposure pathways, inhalation is the most important and dominant one. The risk assessment conducted in this study focused mainly on the onsite workers (as the site was located in remote area). However, if the site is located in the close proximity of offsite receptors, it is recommended that offsite risk should also be estimated. The daily intake of the contaminant was calculated using equation below.

$$\text{Daily intake} = \frac{\text{C} \times \text{CR} \times \text{EF} \times \text{ED} \times \text{RR} \times \text{ABS}}{\text{BW} \times \text{AT}} \quad (3)$$

Eq. (3) is developed considering inhalation mode of exposure. While calculating the daily contaminant dose using this equation, one of the assumptions used was that a landfarm operator works for a total of 100 days a year for 6 years throughout his life span. For exposure and risk characterization, an attempt has been made to obtain the site-specific data, however, whenever any of these data were not available, the average American adult

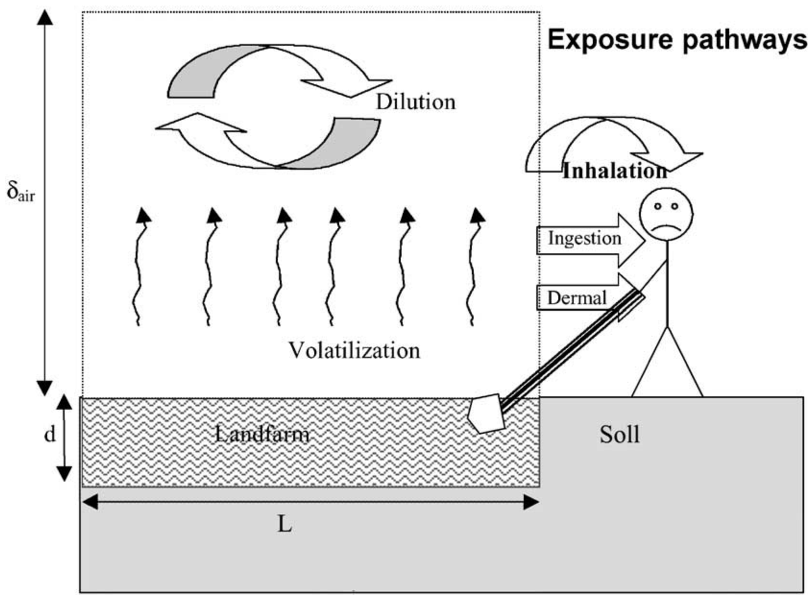

Fig. 3. Conceptual model of the site and exposure pathways.

Table 2
Input data used in the risk assessment study

Parameters	Values			
Characteristics of the experiment cell				
Length of the cell (cm)	200			
Width of the cell (cm)	200			
Thickness of the cell (cm)	30			
Sludge characteristics				
Density of the soil (g/cm^3)	1.80			
Water content in soil (cm^3 water/cm^3 soil)	0.05			
Air content in soil (cm^3 air/cm^3 soil)	0.33			
Total porosity of the soil (dimensionless)	0.35			
Fraction of organic content (g carbon/g soil)[a]	0.01			
Oil and grease load in the cell (mg/kg)	134747			
Receptor characteristics				
Average ambient temperature (°C)	38			
Air inhalation rate (CR) (m^3 per day)	20.16			
Contaminant exposure frequency (EF) (days per year)	100			
Exposure duration (ED) (years)	6			
Retention rate of the contaminant (RR) (dimensionless)	1			
Absorption fraction (ABS) (dimensionless)	1			
Average body weight of the receptors (BW) (kg)	60			
Averaging time (AT) (days)	600			
Contaminant characteristics				
	B	T	E	X
Henry's law constant (cm^3 water/cm^3 air)[a]	0.22	0.26	0.32	0.29
Carbon–water sorption coefficient (cm^3 water/g carbon)[a]	4.85	8.41	22.42	10.80
Chemical diffusivity in air (cm^2/s)[a]	0.093	0.085	0.076	0.072
Chemical diffusivity in water (cm^2/s)[a]	1.1×10^{-5}	9.4×10^{-6}	8.5×10^{-6}	8.5×10^{-6}
Slope factor (mg/kg per day)[b]	0.029	–	–	–
Reference dose (mg/kg per day)[b]		1.4	0.286	2.0

[a] Data adopted from ASTM [6]; B stands for benzene, T for toluene, E for ethylbenzene, and X for xylene.
[b] Values obtained from LaGrega et al. [24].

data available in the literature were used instead (Table 2). Values of the parameter used in Eq. (3) are listed in Table 2.

8. Risk assessment and characterization

Using observed as well as modeled concentrations; risk factors for different exposure routes (inhalation exposure route is the main) for all four chemicals (BTEX) were estimated. Among these four compounds, benzene is a known carcinogen whereas the others

Table 3
Risk factor for observed and modeled conditions

Date	Observed risk				Modeled risk			
	Carcinogenic	Non-carcinogenic			Carcinogenic	Non-carcinogenic		
	B	T	E	X	B	T	E	X
26 September 2000	2.58×10^{-3}	<1.0	<1.0	<1.0	3.41×10^{-3}	<1.0	<1.0	<1.0
10 October 2000	2.925×10^{-5}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
26 November 2000	1.0×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
17 December 2000	1.0×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
3 February 2001	8.77×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
11 March 2001	5.85×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
9 April 2001	1.0×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
7 May 2001	1.0×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
2 June 2001	1.0×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
8 July 2001	1.0×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0
5 August 2001	1.0×10^{-6}	<1.0	<1.0	<1.0	$<1.0 \times 10^{-6}$	<1.0	<1.0	<1.0

B is for benzene, T for toluene, E for ethylbenzene, and X for xylene.

are non-carcinogens. Therefore, both carcinogen (risk factor) and non-carcinogen (hazard quotient) risks were estimated using Eqs. (4) and (5).

$$\text{Risk factor} = \text{daily intake} \times \text{slope factor} \tag{4}$$

$$\text{Hazard quotient} = \frac{\text{daily intake}}{\text{reference dose}} \tag{5}$$

For calculating the risk factor, the slope factor of benzene was used and for calculating the hazard quotient, the referenced doses of toluene, ethylbenzene, and xylene were used. The used values were adapted from LaGrega et al. [24] and are listed in Table 2. Hazard quotient higher than one and risk factor higher than 1.0×10^{-6} are considered unacceptable.

The calculated risk factors for both approaches are presented in Table 3. From this table it is clear that both approaches (monitored and modeled concentrations) predicted consistently similar results.

The monitored values show that for the first month working in a landfarm, an average worker exposed to a benzene concentration of 0.265 mg/m^3 would have a cancer risk of 2.58×10^{-3} (for a total working life of 6 years). According to the modeled concentration, the calculated risk for the first month is 3.41×10^{-3} (for a total working life of 6 years). These numbers signify that out of 1000 people exposed to this condition 2.58 people are likely to get cancer as per the observed value and 3.41 as per the modeled value. Both values (2.58 and 3.42) are 258 and 341 times higher, respectively, than the acceptable value (1.0×10^{-6}). However, as the concentration of benzene depletes in the following 90 days, the cancer risk to the workers decreases and ultimately reaches the acceptable level of 1.0×10^{-6}.

Based on the above, it can be concluded that the first, 3 months of sludge application poses serious carcinogen risk to onsite workers. However, after this period and as most of these compounds volatilize or degraded, the detrimental risk of these compounds becomes acceptable.

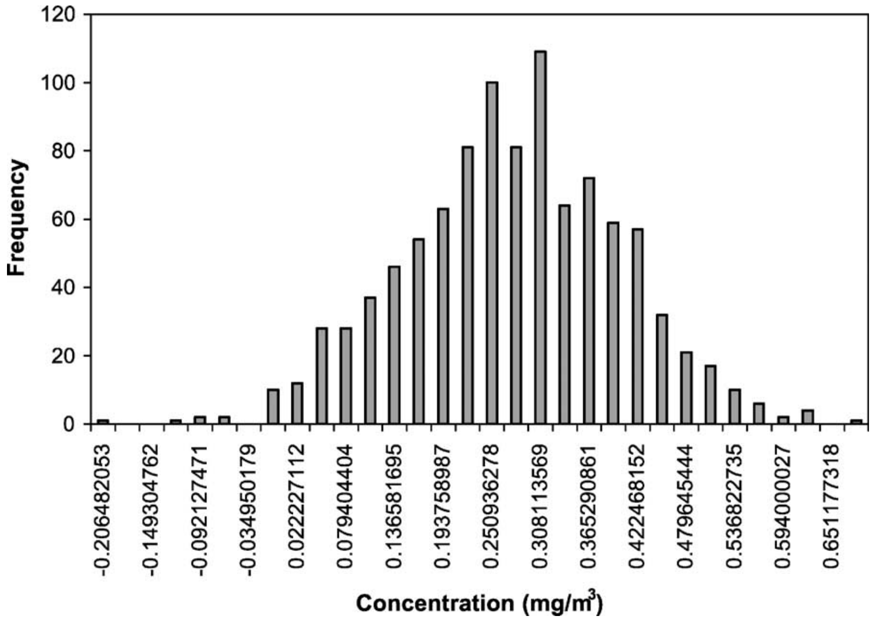

Fig. 4. Probability distribution of benzene concentration (mg/m^3).

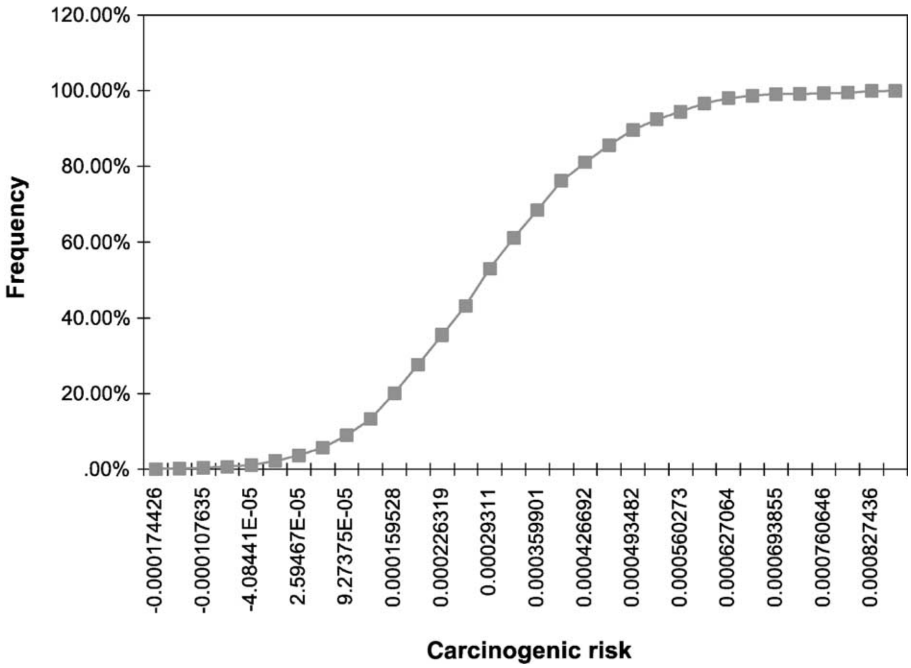

Fig. 5. Cumulative density function for carcinogenic risk due to benzene exposure.

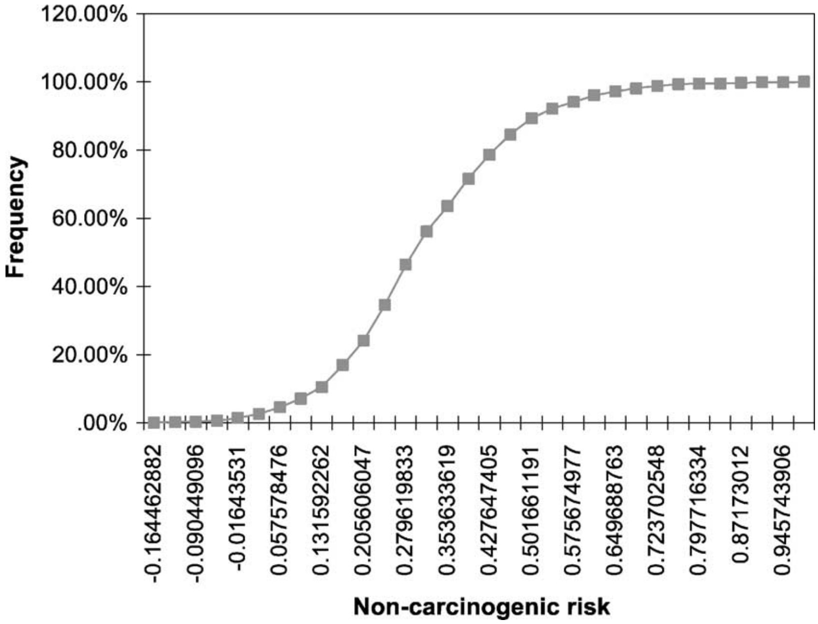

Fig. 6. Cumulative density function for non-carcinogenic risk due to ethylene exposure.

9. Probabilistic analysis

It may not be appropriate to conclude based on a single deterministic value, as there may be substantial uncertainty in each parameter estimation and final computation of risk factor. To deal with this, a detailed probabilistic risk assessment was conducted using Monte Carlo simulation method (US EPA recommended method for probabilistic analysis) [7].

It was considered that monitored concentration inherits an uncertainty of 50%, and other parameter, such as contact rate (CR), exposure duration (ED), and body weight (BW) have an uncertainty of 20% under normality assumptions. Based on these uncertainties, probability density functions were developed, similar to one shown in Fig. 4 for benzene concentration. These probability distributions are subject to Monte-Carlo simulation as per the relationship shown in Eqs. (3)–(5) to calculate carcinogenic and non-carcinogenic risks. Figs. 5 and 6 depict the probability density as well as cumulative density function profile for carcinogenic risk (benzene) and non-carcinogenic risk (ethylene). It is observed from the figure that 95 percentile of carcinogenic risk is 5.6×10^{-4} which is far higher than acceptable level (though lower than single deterministic value), whereas the non-carcinogenic risk is 0.59 which is within acceptable limit.

10. Conclusions

The conducted risk assessment clearly showed that landfarming at the study site pose detrimental risk through the air pathway (through the inhalation exposure route) to site workers for initial period of the landfarming. Since this assessment was conducted on a small cell (2 m × 2 m), the obtained results should be extrapolated for any large size landfarms in similar arid and hot regions. The important conclusions drawn from this study include

- Landfarm activity poses serious onsite risk (for initial periods) and may also pose serious offsite risk, particularly at the initial period of the loading. If the loading is on a continuous basis, the initial period may be sustained for a long time.
- Tilling activities will enhance volatilization, and this will further add to the risk potential to field personnel.
- The ASTMs volatilization and dilution model was able to represent the monitored values appropriately. It is believed that this methodology along with the model can be used for the risk assessment of any landfarm. However, additional models need to be incorporated for offsite transport and exposure.

From the above conclusions, the following recommendations are made:

- To select and design any landfarm, a detailed risk assessment analysis must be conducted to ensure that it does not pose a significant risk to onsite and offsite receptors.
- Safety guidelines must be developed for onsite landfarming activity and must be strictly followed.
- The results discussed in this paper is for initial 13 months of the study, it is likely that most of the scenario mentioned in the paper such as leaching, metal migration, and air borne risk, will not change significantly in subsequent time. However, this fact has to be ascertained by extending the study for another period of 13 or 24 months.

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