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Original Research Paper

A Fuzzy Logic Model to Determine Petroleum Hydrocarbons Concentration at Different Depths of Contaminated Soil During Phytoremediation

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ABSTRACT

Phytoremediation is a cost-effective, efficient and environment-friendly biological method to reduce petroleum-based contamination in soil. However, limited access to soil samples from various depths during phytoremediation along with the cost, time and effort required for quantitative measurement of total petroleum hydrocarbons (TPH) necessitates the development of a mathematical model to overcome the existing obstacles. Since fuzzy logic is an appropriate method for meddling systems with inadequate or vague and non-specific information, the present study sought to determine TPH concentrations during phytoremediation through such a technique. Based on previous research and the conditions of areas adjacent to Isfahan Oil Refinery (Isfahan, Iran), sorghum and barley were planted in 130 cm long polyvinyl chloride pipes containing contaminated soil samples from the mentioned area. After 17 weeks, TPH concentrations were measured at 25, 50, 75, and 100 cm depths of soil. The percent reduction in TPH concentrations was 23%-35% higher in the presence of sorghum and barley than in unplanted treatments. Fuzzy inference with two inputs (time and depth) and 10 membership functions was used to quantify TPH concentrations (the output) at different depths of planted and unplanted soils during the phytoremediation process. Since the calculated and measured values were consistent, the developed model can be applied in future phytoremediation studies in other contaminated areas.

INTRODUCTION

Isfahan Oil Refinery (Isfahan, Iran) is responsible for the production of huge amounts of oil waste. As the released organic compounds are highly toxic, carcinogenic and mutagenic, they can potentially contaminate the soil and groundwater resources of the adjacent area. This is particularly important in Isfahan where arid/semi-arid climate has limited the access to adequate surface water resources. On the other hand, since groundwater restoration is time-consuming and costly, petroleum-based contaminants in lands near Isfahan Oil Refinery have to be treated before reaching the existing aquifers. Among the various methods proposed for oil-contaminated soil remediation, phytoremediation has been identified as an efficient and cost-effective technique (Newman & Reynolds 2005). Nevertheless, the efficiency of the method is substantially restricted by increased depth of soil and distance from the rhizosphere. In fact, previous research has highlighted the impact of rhizosphere on the reduction of total petroleum hydrocarbons (TPH) in soil (Tang et al. 2012).

Limited access to soil samples from various depths during phytoremediation along with the cost, time and effort required for quantitative measurement of TPH necessitates the development of a mathematical model to overcome the existing obstacles. Fuzzy logic is a feasible method for modelling systems with inadequate or vague and non-specific information (Zadeh 1971). The fuzzy set theory, introduced by Zadeh in 1965, allows the user to define the rules and understand the relations between parameters and the existing decision-making process. Being able to consider a range of possibilities instead of numbers, fuzzy logic combines the advantages of statistical methods with the capability of mathematical formulation of empirical knowledge and is thus a valuable tool for modelling natural phenomena (Pourghasemi et al. 2009).

Consequent to its constant evolution, the fuzzy set theory has found various applications. While fuzzy logic techniques have not been as extensively applied in the environmental field as in other fields such as industrial control systems, their diversity and progression increase their potential to affect environmental policy making. As natural phenomena are generally accompanied by uncertainty, further applied research on the practicality of fuzzy logic in all branches of environmental science (e.g., water resources and soil) is warranted.

Therefore, in recent years, numerous studies have evaluated the application of fuzzy logic methods to assess air quality and pollution (Fisher 2003, Onkal-Engin et al. 2004, Sowlat et al. 2011), quality of surface waters (Ocampo-Duque et al. 2006, Lermontov et al. 2009), fitness of water quality for agricultural purposes (Mirabbasi et al. 2008), health of rivers (Zhao & Yang 2009), and groundwater contamination (Muhammetoglu & Yardimci 2006). The efficacy of the mentioned methods in the identification of hydrologically homogeneous regions (Shu & Burn 2004), predicting soil erosion in watersheds (Mitra et al. 1998), determining the carrying capacity of the rivers (Meng et al. 2009, Gong & Jin 2009), comprehensive environmental assessment (Haiyan 2002), and river water quality classification (Chang et al. 2001, Wang et al. 2008, Lu et al. 2010, Liu et al. 2010) has also been investigated. In Iran, however, fuzzy logic has not been commonly practiced due to the unfamiliarity of environmental experts with the subject. The present study applied fuzzy logic to model TPH concentrations at different depths of soil during phytoremediation. Considering the inaccessibility of all soil depths, high costs of measurement, and the existing ambiguities, such a model will facilitate the evaluation and control of soil contamination.

METHODS

Determining physical and chemical properties of soil: Soil samples were collected from the contaminated lands contiguous to Isfahan Oil Refinery's sulphur recovery unit where oil waste was accumulated. The samples were air dried and ground to pass a 2 mm sieve. Soil structure, electrical conductivity, pH, organic matter, available potassium and phosphorus, cation exchange capacity (CEC) and total nitrogen were measured according to the standard methods (Table 1).

Measuring the concentrations of TPHs and polycyclic aromatic hydrocarbons (PAHs): The concentrations of TPHs and some PAHs were measured by Christopher et al. (1988) method (Table 2).

Phytoremediation experiment: Phytoremediation experiments were conducted in 130 cm long polyvinyl chloride pipes (width: 20 cm) with 20 cm sand filters on the bottom. The pipes had holes at 25, 50, 75, and 100 cm depths to make the final sampling possible. Based on soil bulk density and the volume of the pipes, 45 kg of the collected contaminated soil samples were transferred to the pipes in several stages. The prepared soil columns (n = 9) were planted with either sorghum or barley seeds or left unplanted. In order to assess the resistance and stability of the plants in contaminated soil, they were maintained for 17 weeks after seeding. Since the root tissue was not fully accessible, soil sampling was postponed until the final stages of the study. TPH concentrations at 25, 50, 75 and 100 cm depths of all soil columns were measured 120 days after seeding.

Fuzzy modelling: Data modelling with fuzzy logic was performed in three phases using MATLAB.

***Fuzzification of the inputs and the output*:** The inputs and the output were defined using linguistic variables and membership functions (MF). Depth was defined with four linguistic variables, i.e. very low (0-25 cm), low (25-50 cm), average (50-75 cm) and high (75-100 cm). Time was also defined through two linguistic variables, namely short (0-20 days) and long (20-120 days). The output (TPH concentration) was defined with four linguistic variables including low, average, high and very high. While the Gaussian MF was applied on depth and TPH concentration, the triangular-shaped MF was used for time. The functions were determined following trial and error.

***Defining fuzzy rules and application of fuzzy operators*:** According to the measured values, the fuzzy intersection (Min) and union (Max) functions were used to multiply the inputs and combine the outputs, respectively.

***Defuzzification*:** Defuzzification involves the production of a quantifiable output. As we applied Mamdani fuzzy infer-

Table 1. Physical and chemical properties of control and contaminated soil in the study area.

Characteristic	Contaminated soil	Measurement method
Texture	Sandy clay loam	Hydrometry
pH (1:2.5)	7.3	Thomas et al. (1996)
EC (ds/m)	3.2	Rhoades et al. (1996)
Organic matter (%)	4.7	Nelson et al. (1996)
Total nitrogen (%)	1.3	Bremner & Mulvaney (1982)
$CaCO_3$ equivalent (%)	25	Allison & Moodie (1965)
Available-P (mg/kg)	74	Olsen et al. (1982)
Available-K (mg/kg)	24	Page (1982)

Table 2: Concentrations of the measured polycyclic aromatic hydrocarbons (PAHs) and total petroleum hydrocarbons (TPHs) in contaminated soil.

PAHs	Concentration (mg/kg)
Naphthalene	45
Phenantherene	34
Anthracene	6
Fluoranthene	29
Pyrene	16
Benzo[k]fluoranthene	0.4
Benzo[a]pyrene	0.7
TPHs	75000

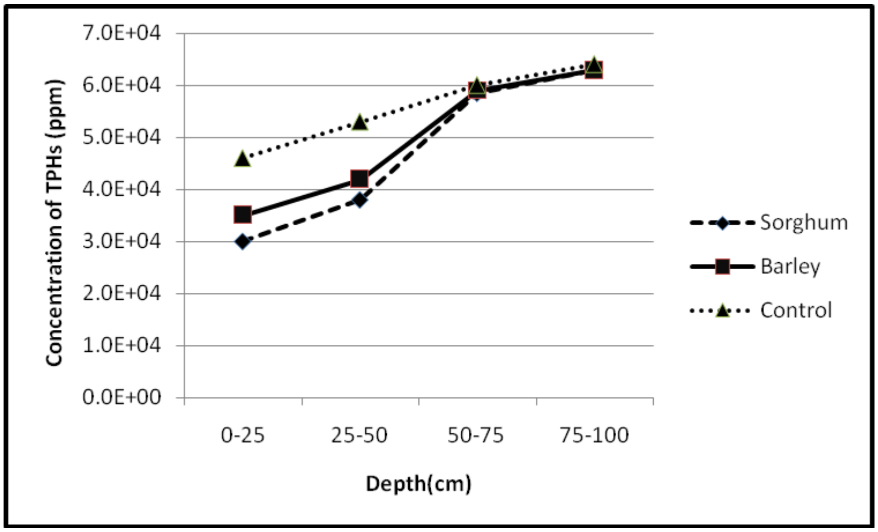

Fig. 1: Changes in the concentrations of total petroleum hydrocarbons at different depths of planted and unplanted soil columns.

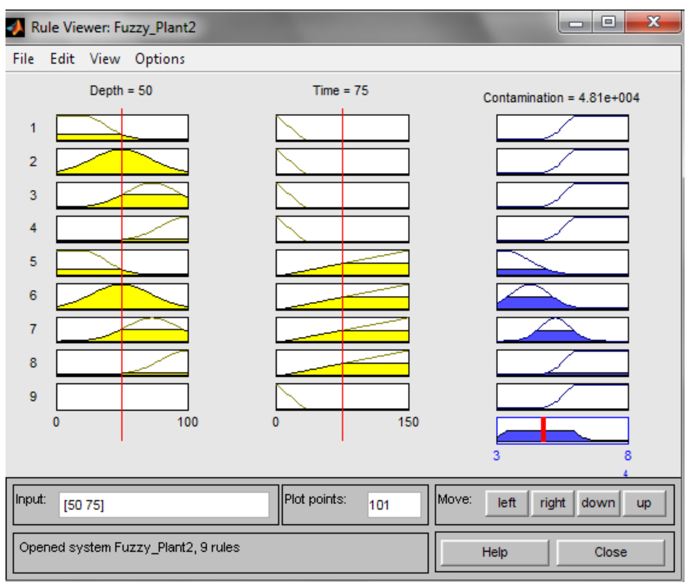

Fig. 2: The inputs and the output of the designed fuzzy model.

ence method, we used the centre of gravity technique for defuzzification. All defuzzification calculations were performed using relevant software and the output was quantified for various inputs.

RESULTS AND DISCUSSION

Fig. 1 demonstrates TPH concentrations in treatments with sorghum and barley and also unplanted (control) treatments. As seen, increasing depth was associated with higher concentrations of TPH and smaller differences between the treatments. More precise, TPH concentrations of control and planted treatments were significantly different at the 0-25 cm depth ($P < 0.05$). However, as both sorghum and barley spread their roots at this depth, no significant difference was observed between planted soil columns. In fact, the extensive root systems of the two species enhanced the microbial activity in the rhizosphere and accelerated the decomposition of petroleum compounds (Hutchinson et al. 2001). Compared to baseline, sorghum and barley decreased TPH concentrations by 64% and 52%, respectively. These values were 23%-35% greater than those detected in the control soil. At the 25-50 cm depth, the difference between TPH

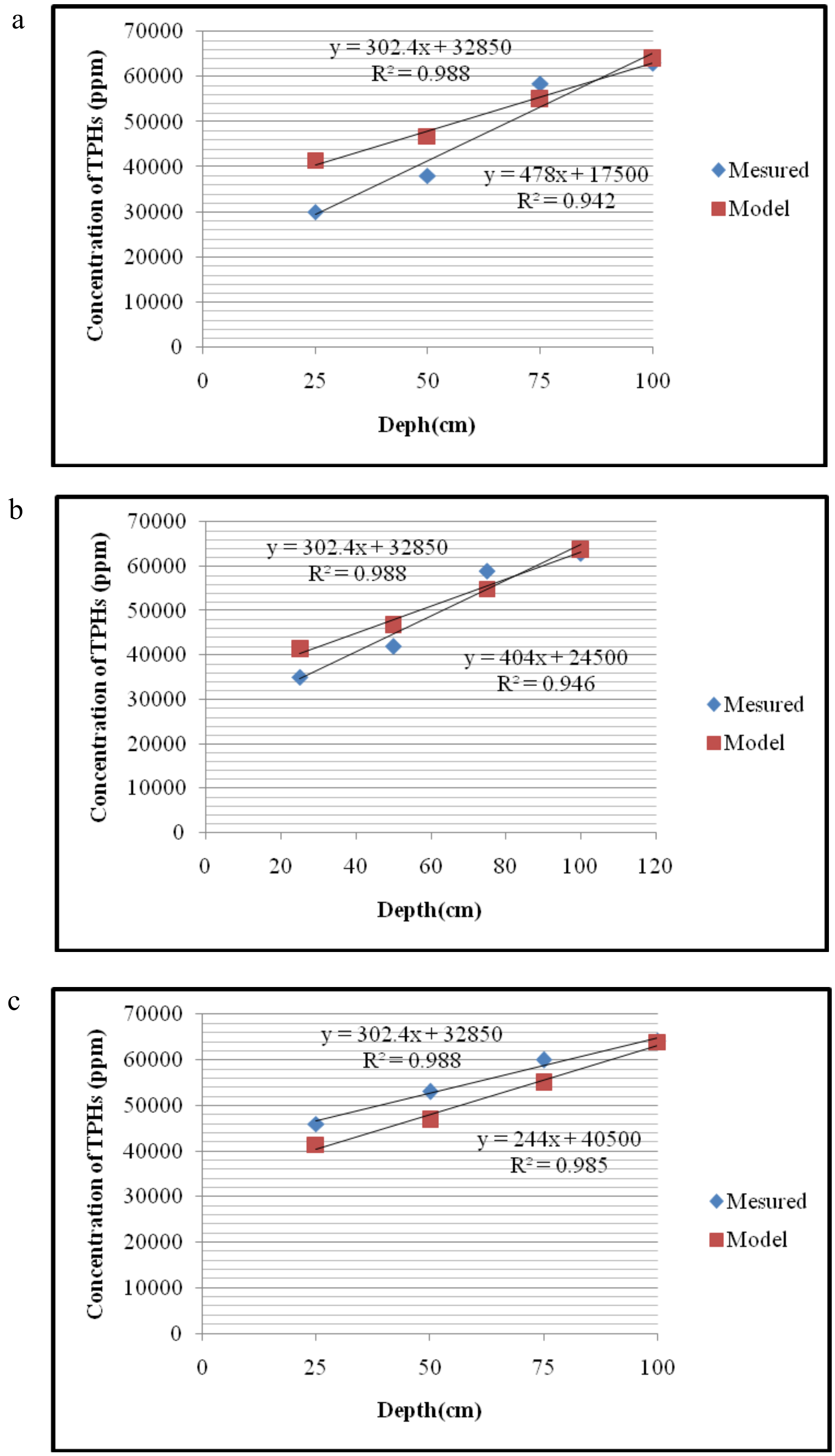

Fig. 3: Comparison between the measured concentrations of total petroleum hydrocarbons and the values obtained from the fuzzy model after 120 days of phytoremediation with sorghum (A), barley (B) and control (C) treatment.

concentrations of the control and planted soils was still significant ($P < 0.05$). Meanwhile, considering sorghum's higher root penetration, the planted treatments were also significantly different in terms of TPH concentration at this depth. At 50-75 and 75-100 cm depths, no significant difference was detected between TPH concentrations of the treatments. In fact, since the roots of sorghum and barley could not penetrate into such great depths, the three types of treatment had almost identical conditions.

After fuzzification of the inputs and the output, defining fuzzy rules and application of fuzzy operators to combine fuzzy relations and aggregate the outputs, and finally defuzzification, the output values were calculated. In Fig. 2, the two inputs are depicted as yellow columns and the output is coloured blue. The red vertical stripes on the inputs are used to determine their numerical values. Consequently, the output for various inputs can be easily obtained.

Figs. 3-5 compare the measured TPH concentrations with the values calculated by the fuzzy model after 120 days. Based on the computed r^2 values, the fuzzy model was well capable of determining TPH concentrations at various depths of soil during the phytoremediation process.

CONCLUSION

The present study designed a fuzzy model to determine TPH concentrations during the phytoremediation process in lands adjacent to Isfahan Oil Refinery. The measured concentrations decreased by 52%-64% in soils planted with sorghum and barley. These rates were 23%-35% greater than the values obtained from unplanted treatments. Since, even small amounts of organic contaminants can seriously threaten human health, enhanced elimination of petroleum-based contaminants in presence of sorghum and barley plays a critical role in improving soil conditions in the area. On the other hand, not only is the quantitative measurement of TPH a difficult, time-consuming and costly task, but it also requires access to different depths of soil during phytoremediation (which is not always possible). Therefore, we determined the concentrations at different times and depths by developing a fuzzy model. The applied model was actually able to mathematically formulate the existing limitations and facilitate decision-making and inference through its simple, flexible concepts.

Considering the novelty of fuzzy logic techniques in soil and water resources studies, particularly in Iran, further, more diverse research on the application of such methods in various fields of integrated soil and water resources management can lead to improved prediction and modelling accuracy at lower cost and time. As the values calculated by our fuzzy model were consistent with the measured TPH concentrations, this model can also be utilized in other contaminated areas. Meanwhile, the model comprised 10 different MFs (four for depth, two for time, and four for the output) whose parameters could be modified by the user and thus alter the numerical value of the output. Since, selecting appropriate values for the parameters is complicated, future studies are suggested to use optimization methods such as genetic algorithms to determine the best parameters for MFs.

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