Chemosphere 83 (2011) 1414–1430

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Review

Fenton based remediation of polycyclic aromatic hydrocarbons-contaminated soils

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ARTICLE INFO

Article history:
Received 21 October 2010
Received in revised form 11 January 2011
Accepted 11 January 2011
Available online 12 February 2011

Keywords:
Polycyclic aromatic hydrocarbons (PAHs)
Soil remediation
Fenton treatment
Modified Fenton treatment
Fenton-like treatment
Integrated Fenton

ABSTRACT

This paper aims to review the applications of Fenton based treatments specifically for polycyclic aromatic hydrocarbons-contaminated soils. An overview of the background and principles of Fenton treatment catalysed by both homogenous (conventional and modified Fenton) and heterogeneous (Fenton-like) catalysts is firstly presented. Laboratory and field soil remediation studies are then discussed in terms of efficiency, kinetics and associated factors. Four main scopes of integrated Fenton treatments, i.e. physical-Fenton, biological-Fenton, electro-Fenton and photo-Fenton are also reviewed in this paper. For each of these integrated remediation technologies, the theoretical background and mechanisms are detailed alongside with achievable removal efficiencies for polycyclic aromatic hydrocarbons in contaminated soils compared to sole Fenton treatment. Finally, the environmental impacts of Fenton based soil treatments are documented and discussed.

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doi:10.1016/j.chemosphere.2011.01.026

Nomenclature

$(OH)C_6H_6^{\cdot}$	hydroxycyclohexadienyl radical
$[H_3O_2]^+$	oxonium ions
≡Fe	surface iron species
AC	alternating current
ANT	anthracene
AOPs	advanced oxidation processes
BAA	benzo[a]anthracene
BAP	benzo[a]pyrene
BAP-1,6-dione	benzo[a]pyrene-1,6-dione
BAP-6,12-dione	benzo[a]pyrene-6,12-dione
BBF	benzo[b]fluoranthene
CDs	cyclodextrins
CHR	chrysene
CMC	critical micelle concentrations
CMCD	carboxylmethyl β-CD
CO_2	carbon dioxide
CP-MF	calcium peroxide-modified Fenton
DAA	dibenzo[a,h]anthracene
DC	direct current
DNAPL	dense non-aqueous phase liquid
DTPA	diethylene triamine pentaacetic acid
EDTA	ethylenediaminetetraacetic acid
EK	electrokinetic
EK-Fenton	electrokinetic-Fenton
EOF	electroosmotic flow
Fe^{2+}	ferrous ion
Fe^{3+}	ferric ion
Fe_3O_4	magnetite
Fe-DTPA	iron chelated diethylene triamine pentaacetic acid
Fe-EDTA	iron chelated ethylenediaminetetraacetic acid
FL	fluorene
FLT	fluoranthene
H_2O_2	hydrogen peroxide
H_2SO_4	sulphuric acid
HEIDA	disodium ethanoldiglycine
HMW	high molecular weight
$HO_2^{\cdot}$	perhydroxyl radical
HPCD	hydroxylpropyl β-CD
HP-MF	hydrogen peroxide-modified Fenton
ISCO	in situ chemical oxidation
KH_2PO_4	potassium dihydrogen phosphate
K_{ow}	octanol–water partition coefficient
LMW	low molecular weight
MCD	methylated β-CD
MGP	manufactured gas plants
NAP	naphthalene
NAPL	non-aqueous phase liquid
NOM	natural organic matter
NTA	nitrilotriacetic acid
$O_2^{\cdot-}$	superoxide radical
$OH^{\cdot}$	hydroxyl radical
PAH	polycyclic aromatic hydrocarbons
PHE	phenanthrene
PKO	palm kernel oil
PYR	pyrene
SBR	sequential batch reactor
SDS	sodium dodecyl sulphate
SOM	soil organic matter
SPS	sodium persulfate
TOC	total organic carbon
UV	ultra-violet
VOCs	volatile organic compounds
α-$Fe_{10}O_{15}{\cdot}9H_2O$	ferrihydrite
α-FeOOH	goethite
α-Fe_2O_3	hematite

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are a class of several hundred individual compounds containing at least two condensed aromatic rings that are known to be toxic, mutagenic, carcinogenic and teratrogenic. They are common pollutants in the environment, and particularly high concentrations are found at sites contaminated with coal tar and creosote, especially as the heritage from the manufactured gas plants (MGP) and wood treatment facilities of the last few centuries. In the United States, for example, there are 1500 former MGP with estimated clean up costs ranging from $1 million to $10 millions per site (Electric Power Research Institute, March 2010). At seriously contaminated sites, the contamination level of PAHs has been reported to be as high as 300 g kg^{-1} soil (Kanaly and Harayama, 2000). PAHs are very persistent showing extended natural attenuation times. The half life of PAHs in contaminated soils can be as long as 5.7 years and 9.1 years for low molecular weight (LMW) and high molecular weight (HMW) PAHs respectively (Wild et al., 1991), thus demonstrating the need for remediation processes to accelerate the clean-up of PAH-contaminated soils. PAHs in soil can be strongly sorbed to soil organic matter (SOM), encapsulated in soil mineral, and can also be present in dense non-aqueous phase liquid (DNAPL), which makes the remediation process difficult.

Many types of remediation technologies have been explored for the removal of PAHs from soils, involving solely one or a combination of physical, chemical, biological and thermal processes (Gan et al., 2009). Faster and more efficient degradation of recalcitrant compounds such as PAHs can be achieved using advanced oxidation processes (AOPs) (Kawahara et al., 1995; Nam et al., 2001; Watts et al., 2002). Fenton treatment is a widely studied technique that is classified under AOPs. The Fenton reagent was developed by Henry John Horstman Fenton in the 1890s (Fenton, 1893, 1894a,b). It has been commonly used as an oxidising agent for organic contaminants in industrial wastewaters since 1960s (Huang et al., 1993; Bautista et al., 2008). However, studies on its potential applications in soil remediation only started in 1990s on a laboratory scale (Tyre et al., 1991; Watts et al., 1991, 1993, 1994; Ravikumur and Gurol, 1994; Karkala and Watts, 1997), and the first study of a Fenton based treatment for PAH-contaminated soil was conducted by Martens and Frankenberg in 1995 using surfactant (Martens and Frankenberger, 1995).

Over the last two decades, Fenton treatment has emerged as a viable remediation technology for PAH-contaminated soils. Several reviews on various Fenton based treatments for contaminated soils have been published (Munter, 2001; Watts and Teel, 2005; di Palma, 2005; Pignatello et al., 2006). In these works, PAHs have been grouped as hydrophobic or semi-volatile contaminants and the discussions presented were broadly for hydrophobic or semi-volatile contaminants. For PAHs specifically, Rivas (2006) in his review on chemical oxidation treatments for soil PAHs briefly discussed the overall considerations in