Reed-Bed Technology for Treating Oil-Production Water in the Sultanate of Oman

Safe and environmentally benign disposal of produced water is a major concern in the Sultanate of Oman. Petroleum Development Oman (PDO) produces 600 000 m^3/d of water, which is contaminated with petroleum hydrocarbons (10 to 800 mg/L), traces of phenols, emulsifiers, and a wide range of metals at varying concentrations. It also shows a relatively high electrical conductivity. The current methods of disposal into shallow and deep aquifers are no longer meeting environmental regulations. The use of reed-bed technology for the treatment of produced water significantly reduced organic- and inorganic-contaminant concentration in the effluents.

Introduction

Oil production in Oman is associated with large volumes of water, termed oil-production water (OPW), and the water/oil ratio can be as high as 1:6 after preliminary separation. The volume of water produced by PDO is predicted to rise to 900 000 m^3/d by 2013. Only 40% of the OPW is used to maintain reservoir pressure by injection, while the remainder is disposed of into shallow and deep aquifers.

Over the last 3 decades, these methods of disposal became progressively unacceptable for various environmental reasons. A major concern was the possibility of contaminating the groundwater resources with toxic organic and inorganic contaminants. PDO's environmental policy is to invest in research projects aimed at better use of the OPW. Water-treatment and reuse plans were developed, driven by the concept of "greening the desert" by use of reed beds to treat the OPW.

This article, written by Technology Editor Dennis Denney, contains highlights of paper SPE 98548, "The Use of Reed-Bed Technology for Treating Oil-Production Waters in the Sultanate of Oman," by ***A. Al Mahruki,*** *Sultan Qaboos U.;* ***B. Alloway,*** *U. of Reading; and* ***H. Patzelt,*** *Sultan Qaboos U., prepared for the 2006 SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Abu Dhabi, UAE, 2–4 April.*

Reed-Bed Biotechnology

There has been increasing interest in environmental biotechnologies because of their potential in removing organic and inorganic contaminants from soil, water, and waste water. For instance, reed beds are used to treat water, waste water, and effluent from different sources including household, agricultural, industrial, and mining effluents contaminated with toxic organic contaminants and heavy metals. Recent literature on phytoremediation discussed the interaction between the soil matrix, plants, and microbial population that brings about many processes responsible for cleanup of contaminants including phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization.

Materials and Methods

A large-scale reed-bed system was set up in Nimr, in south Oman. It comprised eight beds, with each reed bed being 75×48 m (3600 m^2). Each line of four reed beds is called a train and is expected to treat 1500 m^3/d after the reed beds have matured. Initially, two trains were constructed (Train A and B) to treat 3000 m^3/d with gradual expansion to 170 000 m^3/d.

The beds of each train were set at different elevations, such that the primary reed beds, A1 and B1, were highest to promote sequential water flow by gravity through the four beds in each train. The beds were lined with either high-density polyethylene (Train B) or bentonite (Train A) for specific functions. The last three evaporation beds in Train B were originally intended to enhance evapotranspiration as an alternative method of disposal. However, their function was reoriented to further polish the effluents leaving the primary reed bed (B1), thereby allowing good-quality effluents for use in saline agriculture.

The beds were filled with a mixture of desert topsoil, bentonite, chopped hay, and sewage sludge at a ratio of 8240, 140, 320, and 100 m^3, respectively. The first two constituents were expected to play a major role in metal uptake, especially the desert soil that was rich in various oxides, $CaCO_3$, and other clay minerals such as palygorskite and illite. The latter two were added to enhance microbial activity. The beds were planted with a common reed, *Phragmites australis,* known to be tolerant of a very wide range of water conditions and having been used widely for wastewater treatment. The plants are very effective in transferring oxygen to significant soil depths. They also are characterized by having high organic-matter productivity.

The water-flow regime is subsurface. Beds are kept saturated, with the water level just below the soil surface, by use of an adjustable arm (level pipe). Frequently, the level may have to be raised to counteract any salinity effects on the plants within the system. Typical rates of application to the system were intended to be 0.05 $m^3/m^2{\cdot}d$ at the beginning and were expected to rise slowly over the trial period by 4 to 5 times this value.

Within each reed bed, the inlet water is introduced above the gravel ditches, at 12-m spacing, and then seeps down to the bottom of the bed. When the ditches are saturated, water starts to seep laterally for a distance of 6 m toward two parallel drainage pipes (outlets) at the bottom of the bed. Then,

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the cleaned water flows by gravity from the primary-treatment reed bed (B1) to B2, then in a similar manner to B3 and finally to B4. As water passes through each bed, water evaporates and the salinity level increases. The residual effluent is then pumped to a sprinkler system and flows to open-pan evaporation ponds set up to process 400 m^3/d of water for salt production.

Sampling and Analyses. Eight liquid and four solid samples were collected at different time intervals over the 3-year monitoring period, 2000 to 2003. Two 1-L influent and effluent samples were collected for each bed for organic and inorganic analyses. Samples were aqua-regia digested by use of a laboratory microwave-digestion system that was used to extract hydrocarbons from soil and plant samples.

Results

The discussion is limited to the performance of Train-B reed beds.

Wastewater Quality. Analysis of the OPW confirmed the presence of a wide range of contaminants: organic, inorganic, and diverse suspended mineral and organic particulates. The contaminants were found to vary from one location to another and at the same location with time. The variation in the concentration of organics was attributed to the performance efficiency of the preliminary-separation technique. Typical variations in the amount of oil in water in Oman fluctuate from 10 to 800 mg/L. The quality of the OPW does not meet Omani standards for agricultural reuse; therefore, treatment is necessary.

Change of Physicochemical Parameters. The removal of biochemical oxygen demand (BOD) and turbidity was achieved within the primary-treatment reed bed, B1. Thereafter, levels remained within a narrow range in the effluents percolating through the other three beds. The BOD removal was inconsistent either with time or along the train of reed beds throughout the monitoring period.

Generally, the effluent values were lowered by approximately 50%, which is within the removal range for most systems depending on the inlet concentrations, depth of the root system, and temperature. Other parameters, such as pH of the inlet and outlet water, remained almost unchanged, but the values of total dissolved solids, electrical conductivity, and Cl were considerably elevated as water percolated through the sequence of the four reed beds as a result of high evapotranspiration rates under the high temperatures of the desert climate.

Removal of Inorganic Contaminants. The highest removal rates were achieved for Al, Ba, Cr, Cu, and Zn at percentages ranging between 40 and 78%, and up to 40% for Fe, Li, Mn, Pb, As, Cd, Co, Mo, Ni, Se, Ti, and V. Their removal was achieved mainly by the substrate and the growing macrophytes, which acted as an efficient sink in the retention of metals.

Removal of Organic Contaminants. As with BOD and turbidity, the attenuation of petroleum hydrocarbons was achieved principally by the primary reed bed (B1). The remaining three beds further reduced influent concentrations to well below 4 mg/L. The result was an average removal of 96% for the 3 years of operation, regardless of the variation in influent concentration. Oil was removed from the water by three major retention mechanisms: Soil matrix retained approximately 15 mg/kg without any further significant accumulation over time; the sediment layer and above-ground parts of growing reeds retained oil by as much as 36±9% and 43±13% of their weight, respectively; and macrophytes were found to take up and translocate hydrocarbons in a sequential manner to above-ground vegetative parts averaging approximately 10 mg/kg.

The well-developed sediment layer and the vigorously growing reeds seemed to act as efficient filters. They physically entrap and sequester most of the incoming hydrocarbons introduced by inlet production water, and, with time, they became the major sinks within this ecosystem. As a result, the hydrocarbons were limited from reaching the original mineral-soil matrix, which probably facilitated their rapid dissipation by various biotic and abiotic processes. Therefore, hydrocarbons retained by the sediment layer and the creeping on the stem of the reeds were subjected to active aerobic biodegradation and intense weathering processes such as volatilization and photo-oxidation that were usually greater in summer than in winter.

The common reed appears to take up and degrade hydrocarbon compounds through various metabolic pathways within the plant, transforming and mineralizing them into less toxic forms through phytodegradation similar to that of other phytoremediative plant species. It is also believed that reeds facilitated the volatilization of hydrocarbons, particularly the lower-molecular-weight compounds, through their high evapotranspiration rates, a process known as "phytovolatilization." If so, then it might be even more significant under desert conditions. The role of the root-associated bacteria in enhancing the metabolization of organic contaminants has long been recognized as rhizosphere-enhanced biodegradation. Roots appear to provide an ideal environment for the associated bacteria by supplying them with various readily usable substrates, water, oxygenation, and other nutrients. It is believed that the high input of organic matter and simple substrates; nutrients such as nitrogen, phosphorous, and potassium; ample hydrocarbons; and warm temperatures provided a favorable environment for bacterial populations to flourish.

Nimr Shortfalls and Solutions. The Nimr system has operated below its expected capacity by approximately 65%, and some metals do break through at very low concentrations in the effluents. Soil settling and compaction during the early stages of bed preparation, including soil filling and the subsequent operation and watering, probably caused this shortfall. Finer particles, especially clays, might have translocated down the soil profile and become compacted before the reed roots became established and reached maturity, thus restricting root-soil exploitation. The result was nonuniformity in the subsurface water flow, causing surface flow to dominate the system.

Train A was renovated with coarser soil matrix, and its treatment capacity was improved. Train B has been treating OPW for 5 years, and the effluents are used for growing halophytes such as Atriplex, Henna, and Acacia.

Research has demonstrated that reed-bed technology is feasible and resilient in treating OPW. The quality of the treated effluents meets the Omani guidelines for wastewater reuse in agriculture. JPT