

Reedbeds: A Viable Biotechnology for Transforming Wastewaters into Valuable Asset in Arid Countries

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Abstract

Due to the rapid increase in population accompanied by the limited good water resources, the deterioration of water quality by various contaminants is a major concern in all arid and semi-arid regions of the world. This is further exacerbated by the poor perception and concern of wastewater treatment and reuse.

In the Sultanate of Oman, large quantities of oil production waters (OPWs) are produced as by-product from oil fields, reaching a total volume of one million m³/day. These wastewaters are contaminated with 10-800 mg L⁻¹ petroleum hydrocarbons and a wide range of metals at relatively low concentrations. With a typical EC of 12 dS m⁻¹ they are only moderately saline but often contain organic and inorganic suspended particles. Despite growing environmental concerns, re-injection into deep or shallow aquifers is currently seen as the only viable option for disposal.

An innovative reedbed technology was evaluated at field scale to treat 3000 m³/day of OPWs. A substantial reduction of the concentrations of potentially toxic heavy metals (down by 80%) and total hydrocarbons (96%) proved the effectiveness of the treatment. The quality of the cleaned water is in conformity with Omani wastewater standards for agricultural reuse. This was achieved by the combination of various biological, chemical and physical processes taking place between the substrate, the common reed and root-associated micro-organisms.

Apart from the ecological and aesthetic benefits, five years of uninterrupted operation demonstrated the sustainability of the system. The slightly saline effluents are now available to either directly grow salt tolerant plants or – after desalination – for fresh-water aqua- and agriculture. A country-wide application of the new protocol for reedbed OPW decontamination would not only create substantial revenues for the local communities and save annually re-injection costs of more than 10M\$, but would also effectively decelerate the depletion of valuable ground water resources.

Keywords: Production waters; reedbeds; heavy metals; hydrocarbons; phytoremediation; saline agriculture.

Introduction

Water is undoubtedly the most precious resource on earth as its availability and quality determines mankind well-being and even existence. This is especially evident in arid and semi-arid countries that suffer from water scarcity and/or the deterioration of water quality by elevated levels of salinity and other organic and inorganic toxic contaminants. Water degradation influences our environment, daily lives and our

economy as it costs millions of dollars of the total GDP in developing countries (De Vries and Molden, 2002). One of the most common sources of groundwater contamination comes from activities associated with oil exploration, production, transport and processing. Despite the fact that developing countries suffer water scarcity and quality degradation, wastewater treatment and reuse is less than 15%. This is related to various reasons of which the most predominant is the lack of economic value of water. Consequently, large volumes of domestic, agricultural and industrial wastewaters are disposed of into the environment and end up contaminating exploitable clean water resources such as ground waters. In Oman, for example, the major source of wastewater comes from oil fields where water is produced along with oil as by-product after preliminary separation at ratios as high as 1 to 6 (oil to water). The produced water is expected to rise from 600,000 m³ d⁻¹ to 900,000 m³ d⁻¹ by 2013. Almost 60% of this water is disposed of into shallow aquifers (SWD) and into deep aquifers (DWD) and the remaining 40% re-injected to maintain reservoir pressure. However, disposal into aquifers environmentally unacceptable due to concerns related to the possibility of contaminating the precious exploitable ground water resources with toxic organic and inorganic contaminants. The thorough assessments and evaluations conducted by Petroleum Development Oman (PDO) to look into alternatives revealed that reedbed technology has the potential to treat OPWs and the treated effluents may be then utilized for agriculture.

The setting-up of this project has therefore been based on sound, logical and scientific grounds aimed at converting wastewater to valuable resources as driven by the concept of “Greening the Desert”. The scope of this paper is the evaluation of cheap and environmentally friendly reedbeds to transform oil production wastewater to a resource that meets Omani criteria for agricultural development.

Overview of reed beds biotechnology

Reed beds have been effectively implemented to treat waters, wastewaters and effluents from domestic, agricultural and industrial sectors contaminated with toxic organic and heavy metals (Surface, 1993; Haberl 1999; Trapp and Karlson, 2001). These systems have been recognised as environmentally sound, cheaper than conventional systems and can be sustainable (Raskin and Ensley 2000; Solano *et. al.*, 2004). Henry (2000), revealed that the interaction between the soil matrix, plants and microbial population brings about many processes responsible for the clean-up of contaminants. These include; phytoextraction, phytostabilization, rhizofiltration, phytovolatilisation. He described this innovative technology as a “green revolution”.

Fortunately, the applications of this technology in developing countries has been progressively diversifying which signify that the advances in adapting this technology are likely to proceed and thus exert a positive impact on our environment and sustainable development.

Materials and Methods

Eight beds (75m W and 48m L) were constructed in Nimr area south of Oman (2053 500 N, 375 000 E) comprising a total area of 3,600 m² to treat 3000 m³/d with

the intention to gradually expand the project to accommodate 170,000 m³/d of production water associated with 30,000 m³/d oil production at Nimr. Four beds were lined in a row to form train A and B, where the primary treatment reed beds (A1 & B1) are set at the highest elevation so that water flowed by gravity to the remaining three beds of the train (Fig.1). All beds were lined with either HDPE for the treatment reedbeds or with bentonite for the saline agriculture beds and were then filled with a mixture of desert topsoil, bentonite, chopped hay and sewage sludge at the ratios of 8240, 140, 320 and 100 m³, 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 and CaCO₃ and other clay minerals, while the latter two were added to enhance microbial activity. Finally, the common reeds *Phragmites australis* was planted in the treatment reedbeds because it is known to be tolerant to a wide range of contaminants and water conditions and has therefore been used in wetlands for wastewater treatment.

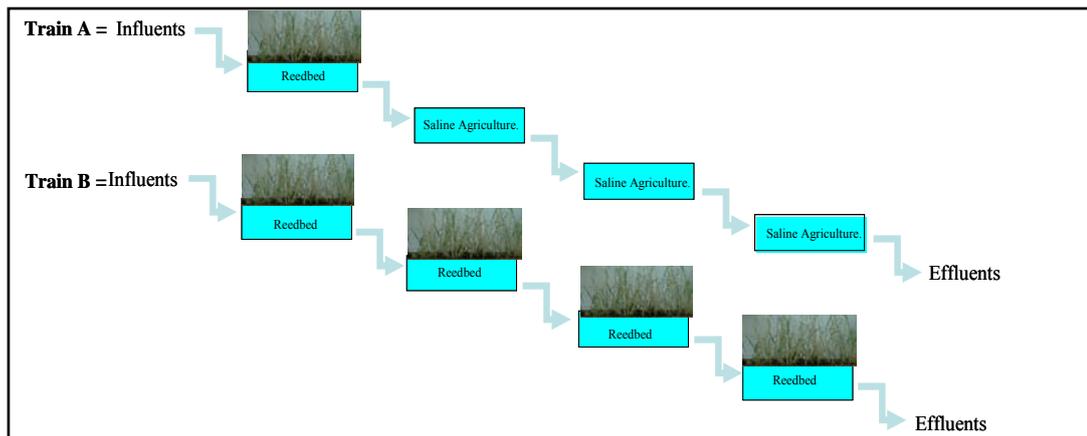


Fig. 1 Schematic layout of Nimr's train A & B reed beds

Reed beds were kept saturated with the water just below the soil surface through an adjustable arm (level pipe) with initial rates of application of 0.05 m³/m² d, expected to increase as the system matured. The raw water was introduced above the inlet gravel ditches located every 12m. The water was then allowed to seep laterally towards the outlet (drainage) pipes located alternately parallel to the inlet ditches at a distance of 6m at the bottom of the bed. Accordingly, the cleaned water would flow by gravity from the primary treatment reed bed (B1) to B2, B3 & B4, respectively. The system's flexibility allows cleaned water leaving each bed to be tested for saline agricultural trials. The remaining residual effluents leaving each train were then pumped to a sprinkler system for further evaporation and finally flow to an open pan evaporation ponds that had been set up to process 400 m³/d for salt production.

Sampling and Analyses

Eight liquid and four solid samples were collected at different time intervals over the monitoring period of three years. The influent and effluent samples were

collected from each bed for the analyses of (i) inorganic and organic analyses according to methods described by Eaton (1995) and (ii) BOD₅ after Slevogt, (2000). The soil and plant samples were aqua-regia digested using a laboratory microwave digestion system (Milestone ETHOS SEL Lab-station), programmed at two temperature stages according to the manufacturer's instructions (ETHOS SEL, 1999). Elemental composition and petroleum hydrocarbons were analysed using a Perkin Elmer (PE) Optima 3300 Dual View ICP-OES and a GC-MS (Shimadzu 17A, equipped with an AOC-20i/20s auto-sampler), respectively.

Results and Discussion

Wastewater Quality

The raw water was contaminated with a wide range of organic and inorganic contaminants that can be broadly grouped into (i) inorganic; Na, B, Sr, Cd, Al, Ba, Cl, Cd, Cr, Cu, Co, Fe, Li, Mn, Si, Zn, Pb, Ag, Se, Hg, As and Ni at concentrations ranging from 10 to 10⁵ µg L⁻¹, (ii) organic; petroleum hydrocarbons in a range of 20 to 800 mg L⁻¹ and (iii) a suspended mineral and organic particulates. Wastewater as such does not meet the Omani standards for agricultural reuse.

The monitoring of some of the physicochemical parameters indicated that the removal of both BOD and turbidity have been primarily achieved with the main treatment reedbed (B1) while the remaining beds acted as polishing beds (Table 1). The 50% reduction of the BOD₅ seems to be within the acceptable or achievable range for many systems depending on the inlet concentrations, depth of the root system and temperature (Campbell and Ogden, 1999; Tanner et al., 1998; Bastian and Hammer, 1993). Other parameters like pH of the inlet and outlet water remained almost unchanged, but the values of TDS, EC and Cl were considerably elevated as water percolated through the sequence of four reed beds due to the high evapotranspiration under the high temperatures of the desert climate.

Table 1 Main physicochemical and biological parameters of the inlet and outlet samples.

Sampling site	BOD ₅ (mg L ⁻¹)	Turbidity (NTU)	EC (dS/m)	TDS (mg L ⁻¹)	Cl (mg L ⁻¹)	PH
Inlet	92 ± 4	198.6 ± 133	10.9 ± 0.7	6985 ± 912	3178 ± 84	8.3 ± 0.5
B1 Outlet	52 ± 5	0.4 ± 0.2	17.7 ± 3.1	12054 ± 2310	4235 ± 829	8.0 ± 0.4
B2 Outlet	49 ± 10	0.3 ± 0.1	16.9 ± 3.3	11729 ± 2769	5008 ± 1027	8.0 ± 0.4
B3 Outlet	45 ± 6	0.4 ± 0.1	20.5 ± 3.3	14351 ± 2626	6810 ± 954	7.9 ± 0.4
B4 Outlet	46 ± 5	0.3 ± 0.1	28.0 ± 11.2	20513 ± 10891	7798 ± 1122	8.0 ± 0.4

Note; All calculations were based on the average samples number (n= 8) except for turbidity (n=4) for 4 years

Removal of inorganic contaminants

The highest removal rates were achieved for Al, Ba, Cr, Cu, and Zn at percentages ranging between 40-78%, less than 40% for Fe, Li, Mn, Pb and further appreciable reductions of As, Cd, Co, Mo, Ni, Se, Tl and V (Table 2).

Metals were efficiently retained by the soil substrate reaching a concentration range of 1 to 1000 mg kg⁻¹ depending on the metal within the first year with no further increase in the following two years of operation. This was attributed to the increased

role of macrophytes in metal uptake which was unselective despite being present at low concentrations and at such high pH values. For instance a one year old stand accumulated a total of 4291 mg kg⁻¹ of Al, As, B, Ba, Cr, Cu, Fe, Ni, Pb, Ti, V & Zn. Besides, *Phragmites* has shown a striking ability to uptake and accumulate various salts at higher levels than the soil matrix itself e.g. Na (>4000 mg kg⁻¹), B (\approx 1000 mg kg⁻¹) and Sr but at lower levels than soil matrix. The reduction in the Eh values of the soil matrix from 260 mV at 10cm to - 88 mV at 55cm deep suggests that metals were immobilized by either or both aerobic and anaerobic associated processes. Moreover, in such calcite rich soils, the continuous dissolution of calcium carbonates increases alkalinity that creates suitable conditions for metal removal and precipitation (Bakhti *et al.*, 2001; Barton and Karathanasis, 1998) and thus act as the major controller of metal mobility (Uygur and Rimmer, 2000; Vance and Pierzynski, 2001; Podlesákova *et al.*, 2001). These findings were found to conform to many other similar studies demonstrating the ability of *Phragmites* to tolerate high metal concentrations and salts thus sustaining the system's efficiency (Campbell and Ogden, 1999; Surface *et al.*, 1993).

Table 2 Averaged metal removal efficiencies by the primary reed bed (B1)

Al	SD	Ba	SD	Cr	SD	Cu	SD	Fe	SD	Li	SD
77.7	17.1	63.7	4.9	59.8	8.3	40.5	14.8	26	16.1	-138*	10
Mn	SD	Pb	SD	Zn	SD	B	SD	Na	SD	Sr	SD
-482*	15.1	13.3	20	80.3	16.8	-63.7	7.5	-66	11.7	-71.5	9.6

*Negative values indicate that the concentration of that element was greater in the effluent than influent. The SD denotes for the standard deviation of eight samples.

Removal of organic contaminants

Similarly to the BOD and turbidity, the attenuation of petroleum hydrocarbons was principally achieved by the primary reed bed (B1), while the remaining three beds virtually acted as polishers that further reduced influent concentrations to below 4mg L⁻¹ (96%). The responsible mechanisms in the removal of hydrocarbons were found to be in the increasing order of (i) Macrophyte uptake and translocation, reaching 10 mg kg⁻¹, (ii) Soil matrix retained about 15 mg kg⁻¹ without any further significant accumulation over time and (iii) Sediment layer and adsorption on above ground parts of growing reeds was as much as 36 \pm 9 and 43 \pm 13% (w/w basis). The latter mechanisms evidently show that the well-developed sediment layer and the vigorously growing reeds were primarily acting as efficient filters in the retention of hydrocarbons and probably facilitate their rapid dissipation by various biotic and abiotic processes. These include; volatilisation and photooxidation that are usually greater in summer than in winter (Moore *et al.*, 1997; Salmon *et al.*, 1997; Moore and Ross, 1999), reed uptake and degradation through various metabolic pathways within the plant, transformation and mineralising into less toxic forms through phytodegradation similar to that which occurs in other phytoremediative plant species (Fiorenza *et al.* 2000). In addition, the reeds facilitate the volatilisation "phytovolatilisation" of hydrocarbons particularly the lower molecular compounds through their high evapotranspiration rates (Trapp and Karlson (2001) and enhance their metabolisation through root associated bacteria "rhizosphere enhanced biodegradation" as confirmed by respirometric tests.

The water regime and redox status observed in the Nimr system suggests the co-existence of aerobic-anaerobic biodegradation with a greater potential for aerobic which is advantageous for bacterial activity (Headley et al., 2000; Platen, 2000).

Reed Growth and Development

In this project, the ability of *Phragmites* to grow, develop and uptake inorganic and organic contaminants as well as tolerate high salinity and the extreme desert environmental conditions was a key success factor of this technology. They have grown to significant heights of more than 2.5m and formed very dense stands reflecting their healthy status, which in turn contributed to the input and incorporation of organic matter into the system. This resulted in the formation of the sediment layer which is sustaining the system's efficiency and capacity in filtering the incoming oil. Reeds also play another important role in oxygenating the rhizosphere, a process that enhances metal precipitation and facilitates aerobic biodegradation to progress at much faster rates (Campbell and Ogden, 1999).

Summary

In summary, at the early stages of operation the system was treating approximately 400-500m³ of production water which was 35% of its designed capacity and didn't improve with time as expected due to clogging problems attributed to the use of loamy soil. However, using sandy loam and surface flow in pot experiments revealed this combination is more appropriate as it improved the treatments capacity by ≈10 times while maintaining treatment efficiency and lower effluent salinity. Currently, the quality of the treated effluents meets the Omani standards for wastewater reuse (Table 3), and the effluents are used for growing halophytes such as attriplex, henna and acacia. Other research is being undertaken to (i) evaluate the desalination of the effluents to develop fresh-water agriculture and (ii) assess the possibility of creating revenue from utilization of *Phragmites* for animal feed, producing compost and bio fuels etc.

Conclusion

The Nimr project has demonstrated that reed bed technology is viable for treating oil production waters in arid countries. The removal of organic and inorganic contaminants was achieved through a diverse range of physical, biological and chemical processes taking place within the system that are possible to sustain. However, it is important to stress that the success of such a technology depends on the correct combination of wastewater characteristics, the type of substrate, design and flow regime as well as the right macrophytes that can grow advantageously. Understanding the contaminant removal mechanisms will facilitate the enhancement of performance and sustaining the operational lifetime of the system. Overall, this wastewater treatment technology has proven to have a positive environmental impact by transforming wastewaters into valuable resources that would allow agricultural and industrial development to flourish and benefit Oman and other arid countries.

Table 3 A comparison between influents and effluent quality change as compared to the quality discharge limits of Oman for irrigating vegetables and fruits that are likely to be eaten raw (Standard A).

Parameter	Standard A	Range in production water	Treated Effluents
Al	5000 µg/l	10-1000	141
Ba	1000 µg/l	0-800	93
Cr	50 µg/l	10-100	5.2
Cu	500 µg/l	5-100	16
Fe	1000 µg/l	100-10000	1716
Pb	100 µg/l	5-60	7
Mn	100 µg/l	80-120	636
Zn	5000 µg/l	1-640	31.8
Li	70 µg/l	75-281	456
B	0.5 mg L ⁻¹	2 -7	9.2
Sr	N/A mg L ⁻¹	3.8-6.6	14
Na	200 mg L ⁻¹	2000-2500	7370
TOC	N/A	70-140	< 12
BOD ₅ @ 20°C	15 mg L ⁻¹	40-160	< 40
EC	2 dS m ⁻¹	12-15	28
pH	6-9	7-8.5	8

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ريد بد : تقنية حيوية قابلة للتطبيق لتحويل مياه الصرف إلى أصول نافعة في دول المناطق الجافة

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إن الزيادة المطلقة في التعداد السكاني ومحدودية الموارد المائية الصالحة للاستخدام البشري وتلوث المصادر المائية تثير قلقاً شديداً خاصة في الدول الجافة وشبه الجافة من العالم. ومما لا شك فيه أن الجهل والتخوف من تدوير المياه المستعملة أو الملوثة واستغلالها يزيد بل ويسرع من تفاقم هذه المشكلة. ففي سلطنة عمان يصاحب استخراج النفط كميات كبيرة من المياه تصل إلى مليون م³/يومياً. يتم التخلص من هذه المياه عن طريق حقنها إلى المكامن الجوفية العميقة أو السطحية لعدم وجود بدائل مجدية اقتصادياً وبيئياً نظراً لتلوثها بالهيدروكربونات البترولية بتركيزات تتراوح بين 10 - 800 ملجم/لتر واحتوائها على نسب متفاوتة من المعادن الثقيلة السامة. كما أن هذه المياه مالحة نسبياً حيث أن معدل توصيلها الكهربائي يصل إلى 12 ميليسيمنس/سم وتحتوي كذلك على شوائب معلقة من أصول عضوية وغير عضوية.

ولأسباب تتعلق بشح المياه والقلق البيئي المتزايد من أسلوب التخلص بالحقن خاصة احتمالية تلوث المياه الجوفية الصالحة للشرب دفعت بالشركة المنتجة للنفط لاختبار تقنية أحواض القصب المائي لمعالجة 33000م³ يومياً من المياه المصاحبة للنفط كبديل للحقن. البحوث العلمية التي تواصلت لمدة أربعة السنوات أثبتت قدرة هذه التقنية الحيوية على تخفيض تركيزات المعادن السامة بنسبة تصل إلى 80% والملوثات الهيدروكربونية بنسبة 96%. كما أكدت الدراسات المعملية والحقلية إن العوامل والتفاعلات الكيميائية والفيزيائية والبيولوجية بين النبات والتربة والكائنات الدقيقة أدت إلى التخلص من هذه الملوثات الضارة والسامة.

ولذا فإن المياه المعالجة تتطابق مع معايير السلطنة لاستخدامات الري وتستغل حالياً للزراعة الملحية وهناك بحوث مطروحة للاستفادة من هذه المياه بعد التحلية للاستزراع السمكي وزراعة المحاصيل ذات قيمة اقتصادية عالية. هذا المشروع الحيوي حول جزء من الصحراء إلى واحة خضراء والتوجه قائم إلى توسيع المشروع لتوفير ما

قدره عشرة ملايين دولار في السنة تكلفه حقن المياه إلى المكامن الجوفية والحيلولة دون تسرب هذه المياه إلى مكامن المياه الجوفية الصالحة للشرب.

وأخيرا أثبت هذا البحث النادر أن هذه التقنية صديقة للبيئة وأنها واعدة لمعالجة المياه الملوثة في الدول الجافة وشبه الجافة بتكاليف اقل من الطرق ألتقليديه وبذلك أمكن تحويل المياه الملوثة والتي كان ينظر إليها عالية على البيئة إلى سلعة ذات مردود اقتصادي واجتماعي وبيئي.