Available options for the bioremediation and restoration of abandoned pyritic dredge spoils causing the death of fringing mangroves in the Niger Delta[1]

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In the Niger Delta, estuarine sediments/soils containing pyrite are often dredged to create access for the exploration and exploitation of petroleum resources. The unconfined disposal and abandonment of the resultant sulfidic spoils along canal banks has resulted in environmental degradation principally through soil acidification, heavy metal pollution, flooding, mangrove die back, erosion, and siltation, succession to freshwater plant species, and altered topography and hydrology. Consequently, former mangrove areas have been converted to either bare spoil heaps, grassland or freshwater forest after several years of natural weathering. This paper discusses ways to avert further degradation through bioremediation, restoration and rehabilitation of the affected areas. The socio-economic consequences of exposed sulfidic spoils in the estuarine ecosystem are also discussed.

Acidification, acid sulphate soils, dredging, mangrove, Niger Delta, pyrite, rehabilitation, restoration, sulfidic dredge spoils/sediment.

1. INTRODUCTION

The Niger Delta, which occupies over half of the entire Nigerian coastline possesses the largest mangrove forest in Africa and is also one of the largest wetland in the world. Despite the recognized value of mangroves for shoreline protection, as nursery grounds and source of food for commercial and sports fisheries [1], the acreage of wetland habitat in many areas has been reduced by anthropogenic modifications [2]. Outstanding among these modifications is dredging, with concomitant spoil disposal, and in Niger Delta, this appears to be the most important single cause of alteration of tidal wetlands.

Dredging in this estuarine ecosystem is often carried out to create safe navigable accesses for resource exploitation particularly oil and gas. During dredging, mangrove sediments and soils are removed, placed along canal banks mostly upon fringing mangroves and abandoned, thus killing the mangroves. Several hectares of mangroves fringing most of the creeks where dredging has taken place has been killed likewise. The extent of impacts on the mangroves have not been reported neither has the quantity of abandoned spoils been quantified. For instance, a company dredged about 2 ha of mangrove in order to create access for oilwell drilling, a further 2.4 ha of mangrove was killed as a result of dredge spoil dumping [3]. A major oil producing company in the delta generated approximately 20 million cubic metres of spoils between 1990 and 1996 [4]. It is expected that the amount of abandoned spoils may have increased considerably taking into account the activities of other oil companies, the nearly 50 years of such operations in the delta and the observed high sedimentation/siltation rates which often necessitates frequent maintenance dredging.

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The sediments and soils of the mangrove zone have been reported to contain reduced iron sulphides particularly pyrite [5]. When present in the natural anoxic and undisturbed state under mangrove cover, sedimentary pyrites are known to be innocuous, but their disturbance through dredging and spoil disposal often initiates a cascade of oxidative reactions leading to estuarine acidification. Estuarine sediment acidification and mine spoil drainages have been reported to cause the death of vegetation [6], fish/aquatic biota [7], change in water quality [8] and heavy metal pollution [9-13). Furthermore, the usual practice of placing unconfined sediments continuously along the canal bank beyond tidal inundation has led to the creation of artificial levee. In the process, several kilometers of undulating spoil heaps now characterize the once low-lying intertidal landscape. The resultant change in the topography and hydrology of the area often prevent site re-colonization by native mangrove species. After several years of weathering only acid and metal tolerant plants become established particularly grasses and sedges followed by some freshwater species.

Worldwide, the disposal of pyritic dredge spoils is a major challenge because of the risk of environmental degradation [10, 11, 13-15]. However, the natural microbial succession and colonization of acidic and heavy metal-laden mine spoil heaps [16-17] and dredge spoils [12] underscores their importance in the management of these wastes. Several microorganisms have been isolated from highly acidic environments such as bacteria [18], fungi [19], algae [20] and diatoms [21]. Some of these organisms have been studied for the bioremediation of metal contaminated wastes [22] through biosorption and changes in redox state. Others have considered sulphate reduction processes for the bioremediation of acidity and heavy metals [23-24]. Lovley and Coates [22] had indicated that bioremediation of metals is still at the research stage with little large-scale application. The aim of this paper therefore, is to present the results of a preliminary laboratory study on the bioremediation of acidic and metal laden dredge spoil leachates with the potential of large-scale application through restoration of site hydrology that will enhance bacterial sulphate reduction and to permit volunteer mangrove recruitment. The environmental and social impacts arising from the abandonment of pyritic spoils are also highlighted.

2. ENVIRONMENTAL IMPACTS OF ABANDONED SULFIDIC SPOILS

The abandonment of unconfined dredge spoils has led to a number of environmental impacts such as direct burial and destruction of fringing mangroves and associated fauna, change in topography and hydrology, siltation of navigable canals, flooding and suffocation of mangroves, degradation of water quality, habitat fragmentation and alteration of vegetation (i.e. conversion from mangrove to bare spoil heap and succession to grassland and freshwater vegetation). This problem is often compounded when the spoils contain sulfidic materials particularly pyrite as in the case of the Niger Delta, it could lead to severe acidification with attendant consequences including heavy metal pollution, vegetation dieback, reduced plant/animal/agricultural productivity, corrosion of steel, concrete, and other engineering structures, degradation of surface and ground water quality, mortality of estuarine biota especially fishes and bioaccumulation of pollutant [8, 25-26].

Typically, the tall red mangrove species, *Rhizophora racemosa* fringes the banks of the numerous creeks in the mangrove zone of the delta. During dredging, sediment, soil and vegetation along the proposed right of way (ROW) are removed, dumped over bank beyond tidal influences and then abandoned. This has led to the alteration in the topography and hydrology of the area [27]. As inundation becomes less frequent with increasing elevation, the soil chemistry and hydrology are also altered, resulting in the alteration of vegetation and organisms inhabiting the area. It has been reported that the hydrology of wetlands is highly sensitive spatially to even to minor changes in topography and associated tidal regime [28-29]. With no tidal and freshwater reaching the artificial spoil levee, the salinity of the pore water will now depend on rainfall and rising ground water levels. The salinity will change depending on season; it will become concentrated during the dry season and diluted during the wet season. After several years of leaching/weathering the spoil will become relatively less saline, which tend to favour the growth of invasive species. Typically, the spoils are placed continuously as canal banks, which form barriers to water flow and thereby causing excessive flooding of the mangroves in the backswamp. Mangroves are known to be sensitive to excessive flooding, and are often killed in the process [30].

Furthermore, acidic spoil leachates often drain into the backswamp and stagnate there. The leachates from spoils in the Niger Delta have been shown to contain high levels of heavy metals [12]. High acidity, heavy metals and altered topography, hydrology and salinity regimes may have contributed to the lack of natural re-vegetation in most of the dredge spoil dumpsites. This phenomenon has led to the creation of canopy gaps and vast wasteland (devoid of vegetation) in the otherwise sheltered estuarine ecosystem and several years after dumping, grasses and freshwater swamp forest communities develop in an otherwise mangrove swamp forest.

3. SOCIO-ECONOMIC IMPACTS

The availability of suitable land for housing and farming is a major challenge in the mangrove areas of the delta. The soils are typically low lying (0.8 – 1.2 m above mean sea level) and are seasonally flooded and tidally inundated daily. The major occupation of the natives is fishing. They therefore found elevated abandoned dredge dumps attractive for the establishment of houses, fishing camps and home gardens. Fruit trees such as pawpaw (*Carica papaya*), mango (*Magifera indica*), Avocado pear (*Persea Americana*), Coconut (*Cocos nucifera*) and pineapple (*Ananas comosus*) are commonly cultivated on matured spoils close to human dwellings. Vegetable and other food crops such as okra (*Abelmoschus esculenta*), bitterleaf (*Vernonia amygalina*), flutted pumpkin (*Telfaria ocidentalis*), cassava (*Manihot* sp.), cocoyam (*Colcasia esculenta*) and plantain (*Musa* sp.) are also cultivated on elevated levees or degraded dredged spoil dumps [27]. Some of these crops particularly pineapples have been reported to be tolerant to acid sulphate soils and have been successfully cultivated on elevated sulfidic spoils in other countries [31-32].

In the process of their occupation of abandoned dredge spoil dumps; some natives now reside dangerously close to oilfield installations. Most of the crops planted on dredge spoils with the exception of plantain and pineapples often suffer from poor yields. Beyond this, there is the risk of heavy metal toxicity and bioaccumulation. Mangrove plants have been reported to bioaccumulate heavy metals [33] so are crops grown on sulfidic dredge spoils [34-35].

4. OPTIONS FOR BIOREMEDIATION AND RESTORATION

Soil acidification has been regarded as a major challenge to mangrove restoration worldwide [36-38]. The pH of dredge spoil leachates is often below 3.5 [12]. Such low pH has been found to inhibit mangrove seedling growth [38]. The accompanying high concentration of heavy metals may compound the problem. Ohimain [25-26] had suggested proper handling of dredge spoils to prevent acid formation. This involves the selective placement of spoils in such a way as to avoid/minimize contacts between the causative agents of acidification, namely, *Acidithiobacillus*, pyrite, water and air. In this paper, emphasis will be focused on the bioremediation of acidic and metal laden leachates followed by restoration of site hydrology to permit field application of bioremediation in large scale and to enhance natural mangrove recruitment.

4.1 Bioremediation

In a preliminary laboratory study on the bioremediation of spoil leachates, sulphate reducing bacteria (SRB) was isolated from the bottom layer of recently dredged spoils using modified Baar's medium [39]. The study was carried out under two different pH regimes, a set of leachates, which had a pH of 2 were sterilized using autoclave, while the other was adjusted to pH 6 using 1.0 M NaOH (microcosm 2) prior to sterilization. The leachates were fed into a 500 ml separation funnel inoculated with pure cultures of SRB under reducing conditions and incubated in the dark at a temperature of 28^{o}C for 180 days. Samples were collected monthly from the top of the separation flask into sealed universal bottles using sterile hypodermic syringes. The samples were analyzed for sulphate (turbidimetric/colorimetric), pH, redox potential (Russell's pH/mV equipped with platinum electrodes in combination with Ag/AgCl reference electrodes), sulphide (iodometric methods), heavy metals (Cd, Cr, Cu, Ni, Mn and Zn) (using atomic absorption spectrophotometer) and SRB population [39].

At the beginning of the experiment (day 0), leachates were characterised with high sulphate (5,200mg/l), acidic pH (microcosm 1 only), redox potential (+280mV), while sulphide was not detected. The medium became blackened after 30 days, thus indicating initiation of sulphate reduction activities. The intensity of the blackening increased thereafter up to day 90 when the medium separated into 2 distinct layers, consisting of an upper clear aqueous layer (supernatant) and a lower dark solid layer (pellets). As the experiment progressed, the supernatant became clearer while the pellets became darker. The increased blackening appears to have correlated with the population of SRB. In both microcosms, as the population of SRB increased, the level of sulphate decreased with a correspondingly increase in sulphide and pH values and a decrease in redox potential (Fig. 1). Heavy metal levels of the aqueous layer followed this pattern; it decreased rapidly from Day 30 to Day 180. Apart from the initial lag period observed within the first 30 days of the experiment in microcosm 1 (Fig. 2), the heavy metal removal efficiency was similar in both microcosms (Table 1), which suggests that the SRB was probably acid tolerant. Using acid-tolerant SRB has the added advantage of reducing the cost of alkaline pre-treatment prior to bioremediation.

It was observed from correlation statistics that SRB population was inversely related to sulphate concentration and directly related sulphide concentration and pH [12], it therefore follows that the microbiological process for the bioremediation of acidic and metal laden leachates depends on the reduction of soluble sulphates to insoluble sulphides, leading to the neutralization of sulphate acidity (i.e. increase in alkalinity) with resultant heavy metal precipitation [12]. Apart from the direct formation of insoluble metal sulphides, the increased pH as a result of sulphate reduction can provide an additional mechanism for metal removal since some metals such as Zn, Co, Ni, Mn sulfides are more soluble at low pH than at neutrality or high pH [23].

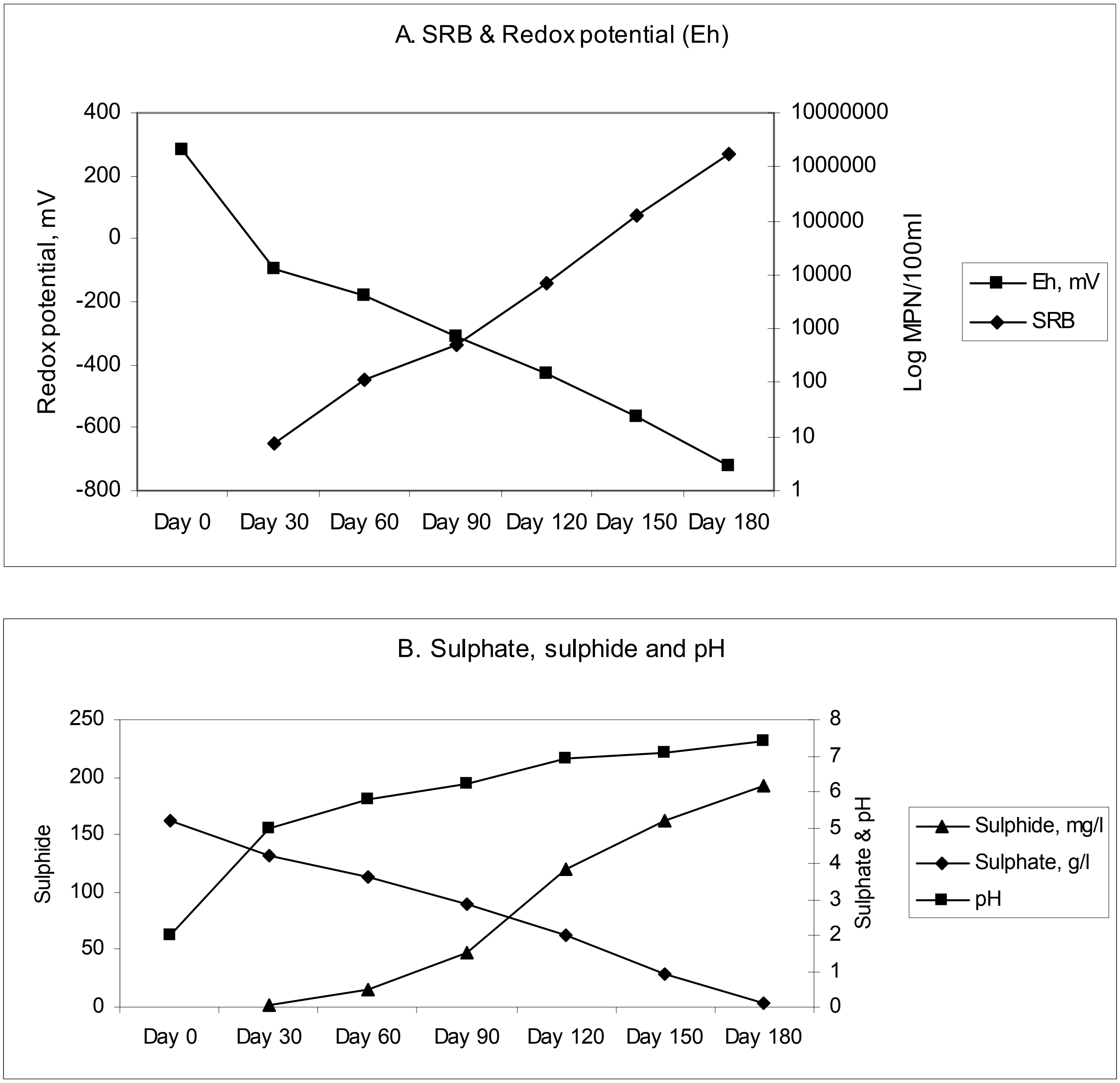

Figure 1: Changes in SRB population, sulphate, sulphide, Redox potential and pH during bioremediation

Table 1: Heavy metal concentration of dredged spoil leachates and precipitation efficiency after 180 days bioremediation treatment

	Initial leachate metal Concentration, mg/l	Precipitation efficiency, %	
		Microcosm 1	Microcosm 2
Copper	82.8	91	92
Cadmium	122.0	90	90
Chromium	53.2	94	96
Nickel	75.3	98	100
Manganese	171.0	99	100
Zinc	113.2	98	99

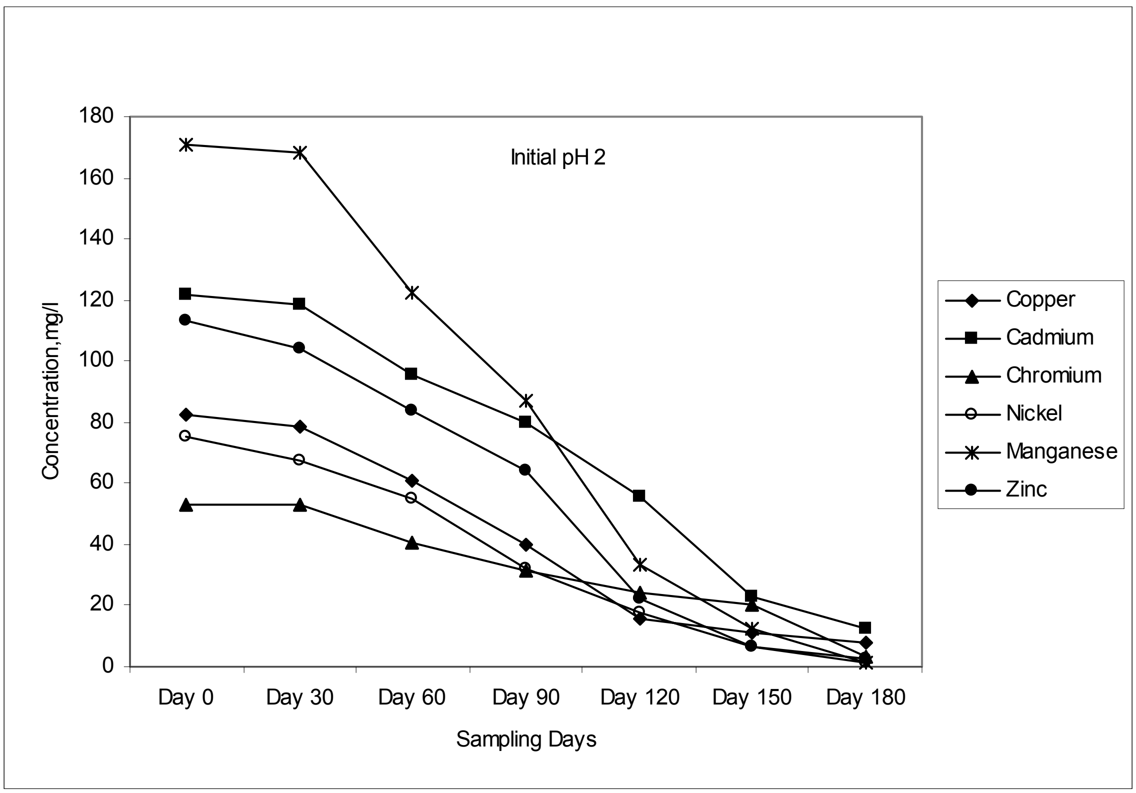

Fig. 2: Changes in heavy metal concentration during bioremediation using acid tolerant SRB

4.2 Mangrove Restoration and Rehabilitation

Ohimain [25-26, 40] had suggested the restoration and rehabilitation of abandoned spoil banks to prevent environmental degradation particularly through acidification. Details of mangrove restoration and rehabilitation techniques are presented elsewhere [40-43], here emphasis will be placed on the restoration of soil salinity, hydrology and topography and also provide a means of creating anaerobic conditions in the spoil banks to permit the growth of SRB for the removal of sulphate acidity and heavy metals (bioremediation), which will permit natural mangrove recruitment.

Prior to spoil abandonment, the topography of the Niger Delta wetlands is 0.8 – 1.2 m above mean sea level [44]. To permit natural mangrove recruitment, the restoration of normal tidal exchange and residence time, site topography and drainage, and freshwater inputs are necessary [37]. This will require site excavation (and grading to pre-spoil disposal elevation) and back filling into disused canals [45] especially those linking dry or exhausted oilwells or other unsuccessful hydrocarbon prospects. This will obviously restore the hydrology, and as the site becomes tidally inundated once again, it will permit removal of oxidation products [37] and since the brackish water of the Niger Delta is well buffered with pH ranging from neutral to slight alkaline (7.0 – 8.4) [40, submitted] the acidity is expected to decline afterwards [46]. Tidal inundation will permit the soils return to anoxic condition found in natural undisturbed mudflats/mangroves [37] and encourage the growth of estuarine bacteria [47] particularly SRB [12]. White et al. [48] suggested rehabilitation of wetlands by re-flooding. Flooding is expected to reverse acidity through microbial catalyzed reactions in which sulphate is reduced to sulphide [49]. Ainodion et al. [50] had used hydrological restoration to successfully re-establish mangroves in the Niger Delta.

5. CONCLUSION

The unconfined disposal of sulfidic dredge spoil is one of the major challenges of the oil industry operating in the Niger Delta. The practice of creating abandoned spoil banks in the estuarine ecosystem has caused a plethora of environmental problems, including direct destruction of fringing mangroves, acidification, heavy metal pollution and alteration in site topography, hydrology and salinity, which prevents volunteer mangrove re-colonization. Through natural weathering processes, the resultant bare spoil dumps continues to release acidic and metal laden leachates into the environment. The result of the preliminary laboratory bioremediation studies appears promising for the removal of acidity and heavy metals. The field application of bioremediation will require the restoration of the normal site hydrology, which will create the required anaerobic conditions for the removal of acidity through bacterial sulphate reduction. Hydrological restoration also has the added advantage of restoring salinity while encouraging tidal buffering and recruitment of volunteer mangrove seedlings.

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