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Vermicomposting of Industrial Organic Wastes and its Application in Mine Rehabilitation Strategies – An Overview from a South African Perspective

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ABSTRACT

Large areas of land are needed to dispose of wastes produced by mining activities worldwide which poses a myriad of environmental hazards with regards to soil, water and air contamination. This is a problem, especially for a mining country like South Africa, where more than 1500 mines are registered which affects 0.2 million ha of land. Legislation in this country do, however, stipulate that disturbed land should be rehabilitated/revegetated but this is both difficult and expensive because of the unavailability of potential topsoil as well as deficiencies in organic matter, elemental imbalances, and absence of essential nutrients. The use of waste and residual organic matter in soil amendment strategies has been well documented with vermicomposting as a prime example of this. Waste woodchips produced by the platinum mining industry in South Africa have been identified as an organic ameliorant during the rehabilitation of platinum tailings. Based on this, several mines in South Africa, including diamond, iron and platinum, were identified where remediation had to be done on tailings dams. This paper gives an overview of the vermicomposting study undertaken and how successful the use of this product was in real world conditions on different rehabilitation strategies from a South African perspective. The presented studies aim to ascertain the feasibility of utilising vermicomposting of industrial organic wastes and its application in mine rehabilitation strategies under South African conditions. Specific objectives included the evaluating the efficiency of utilising vermicompost on platinum, diamond and iron ore tailings dams by determining rehabilitation success. The results presented in this review are based on these studies; some of which have been published already.

Keywords: earthworms, South Africa, vermicomposting, mining, woodchips
Abbreviations: MI, microbial inoculant; **GDP**, gross domestic product; **NDF**, neutral detergent fibre; **PGM**, platinum group metal; **SS**, sewage sludge; **TDF**, tailings disposal facility; **VC**, vermicompost; **WC**, woodchips

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INTRODUCTION

Worldwide, anthropogenic activities such as mining produce large amounts of wastes that create economic and environmental problems. This, due to large areas of land needed to dispose of the wastes, which is expensive and contaminates soil, groundwater and air. Africa produces some of the world's most important minerals and metals including gold, platinum group metals (PGMs), diamonds, uranium, manganese, chromium, nickel, bauxite and cobalt (Mbendi Information Services 2008). The continent also hosts approximately 30% of the world's mineral reserves including 40% of the world's gold, 60% cobalt and 90% of the world's PGM reserves (Mbendi Information Services 2008). From a South African viewpoint, this is important when taking into account the more than 1500 mines Registered and affecting 0.2 million ha of land. Even though mining is important in South Africa, contributing approximately US$ 7.4 billion annually to the countries' GDP (Mbendi Information Services 2008); the costs to the environment are not insignificant. These include environmental impacts such as water pollution, air pollution, soil pollution and generation of domestic and hazardous wastes. Further, the de-watering of aquifers due to shaft and opencast mining; air pollution caused by dust from roads, milling activities and blow-off from tailings storage facilities; air pollution caused by sulphur dioxide and other gaseous emissions during processing of the metals; contamination of soils caused by hydrocarbon spills; soil erosion and soil quality depletion caused by removal and storage of top soils are also possible.

One of the most severe environmental aspects associated with mining is the storage of mineral waste on tailings disposal facilities (TDFs) due to their impacts on air quality, ground water quality, aesthetics and land use. It is also unknown whether the environmental effects of tailings storage facilities increase or decrease over time. This is important when determining the financial liabilities of mining companies in South Africa with regards to tailings storage facilities. The tailings generated as a waste stream during mine-

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ral processing, are essentially a biologically sterile medium with limited water holding capacity. Tailings contain, among others, high concentrations of potentially environmentally non essential toxic elements that can leach into the ground water.

Legislation in this country, with regards to mining, stipulates that all disturbed land should be rehabilitated which often includes revegetation to stabilise the treated soil in an ecologically sustainable manner. The South African National Environmental Management Act (Act No. 107, 1998) states that mines "*must as far as it is reasonably practicable, rehabilitate the environment affected ... to its natural or predetermined state or land use which conforms to the generally accepted principle of sustainable development*" and *"is responsible for any environmental damage, pollution or ecological degradation as a result ... mining operations and which may occur inside or outside the boundaries of the area"*. Although the ultimate goal of these remediation projects might be to return the affected sites to its pre-contamination condition, this is both difficult and expensive because of the unavailability of potential topsoil as well as deficiencies in organic matter, elemental imbalances, and absence of essential nutrients in tailing dams. These problems are currently being addressed by importing topsoil from other areas and treatments with inorganic fertilisers which are both expensive and not ecologically sustainable.

It has been well documented that waste and residual organic matter is excellent to use for soil amendment (Cogliastro *et al.* 2001) because of their organic carbon and nitrogen content (Hartenstein 1986). These characteristics make it ideal sources of essential nutrients to be utilised when revegetating mine tailing dams. The use of vermicomposting to manage organic wastes has been illustrated in numerous studies pertaining to a range of different wastes e.g. woodchips (WC) produced as by-product during platinum mining (Maboeta and van Rensburg 2003a), grape marc (Paradelo *et al.* 2009), municipal solid wastes (various Indian studies cited in a review by Sharholy *et al.* 2008), sewage sludge (SS) and oyster shell (Kwon *et al.* 2009), to name but a few. These studies have all shown that vermicomposting stabilise the nutrients in organic wastes manure and retain them for use in agriculture or alternatively revegetation strategies. This can help to improve environmental quality, since it is a cost-effective solution to waste disposal problems. Vermicomposting can therefore be seen as a technology which turns wastes into a usable commodity and at the same time minimise pollution, since important plant nutrients are released and converted from organic material and in addition there is considerable evidence that human pathogens do not survive the process (Edwards 1995).

Waste WC produced by the platinum mining industry in South Africa has been identified as an organic ameliorant during the rehabilitation of platinum tailings. However, it was found that the addition of WC will enhance vegetation establishment especially during early periods of revegetation, when nitrate is high, but due to possible nitrogen:carbon imbalances further vegetation establishment may be impeded. The need to compost and vermicompost the WC was therefore realised which lead to further investigation (Maboeta and van Rensburg 2003a).

Based on this, several mines in South Africa, including diamond, iron and platinum, were identified where remediation had to be done on tailings dams. The aim of this paper is to give an overview of the vermicomposting study undertaken and how successful the use of this product was in real world conditions on different rehabilitation strategies from a South African perspective. The main aim of the presented studies was to ascertain the feasibility of utilising vermicomposting of industrial organic wastes and its application in mine rehabilitation strategies under South African conditions. Specific objectives included the evaluating the efficiency of utilising vermicompost (VC) on platinum, diamond and iron ore tailings dams by determining rehabilitation success. The results presented in this review are based on these studies, some of which have been published already.

BIOCONVERSION OF INDUSTRIALLY PRODUCED WOODCHIPS AND SEWAGE SLUDGE

In this study the effectiveness of different bioconversion strategies for industrially produced WC *viz*. composting, vermicomposting and micro-organism inoculation were investigated. This was achieved by quantifying the resulting products in terms of chemical and physical changes.

In short, the materials and methods entailed that air-dried samples of WC and SS were obtained from a mine in the North West Province of Southern Africa. The earthworm species used was mature clitellate *Eisenia fetida* whilst a commercial preparation of micro-organisms (MI) was used in the inoculation experiments (predominantly of *Pseudomonas*, *Lactobacillus* and *Saccharomyces* spp). Mixtures of WC and SS with a mixing ratio of 3:1 (dry weight kg^{-1}) were used and moistened with distilled water to a 70% (by weight) moisture content. Five treatment groups with three replicates each were investigated and consisted of WC+SS, WC+SS+MI, WC+SS+earthworms, WC+SS+MI+earthworms and WC mixtures and composted for a period of 28 days. In the treatments with earthworms, 100 mature worms were introduced after the 28-day composting period to avoid exposure of worms to the possible high temperatures during the initial thermophilic phase of composting.

The results indicated that despite low temperatures (33°C) in all the treatments, no *Escherichia coli* or *Salmonella* was detected in any of the end-products. No significant ($P > 0.05$) difference in the mean percentage change of C in the different bioconversion strategies was observed and it was only in the SS+WC and SS+WC+MI groups that the soil available P (P-Bray 1) increase was statistically significant ($P < 0.05$). Treatments containing SS showed significant ($P < 0.05$) decreases in NH_4^+, whereas NO_2^- and NO_3^- increased significantly ($P < 0.05$). The NH_4^+:NO_3^- ratios in the treatments containing SS were lower than 0.16, ranging from 0.011–0.0016, which is an indication of the maturity of the compost. Total solids and ash contents showed an increase, while the volatile solids and the lignin decreased, but it was only in the vermicomposted treatments that these changes were statistically significant ($P < 0.05$). The percentage neutral detergent fibre (%NDF) and %cellulose decreased significantly ($P < 0.05$) in all the treatments containing SS and particle size analysis indicated higher reductions in the vermicomposted treatments. It is concluded that vermicomposting of industrially produced WC and SSis more effective than composting and that the addition of a microbial inoculant did not have a significant effect on the decomposition process.

Further, results revealed that there were no effects on growth ($P > 0.05$), but reproductive success decreased significantly ($P < 0.05$) and Al, Cu and Ni were bioconcentrated ($P < 0.05$) by earthworms in treatment groups without an inoculate. Earthworms in the treatment group with the inoculate did not have an inhibited growth or reproducetive success and did not accumulate Al, Cu, and Ni. It was concluded that an economically feasible way to bioconvert WC and SS would be with the addition of a micro-organism inoculate.

Based on these facts i.e. the nutrient status (**Table 1**; Maboeta and van Rensburg 2003a) and ecotoxicological assessments (**Table 2**; Maboeta and van Rensburg 2003b) the product was produced on a large scale to be applied in real-world rehabilitation strategies. It was, however, found that under field conditions the omissions of the microbial inoculant did not have a significant negative effect on the earthworms and the subsequent production of VC.

Table 1 Nutrient parameters (g kg^{-1}/mg kg^{-1} ± SD) of mixing ratios at the time of loading and after termination of the 112 day trials (n = 9).

Process	TOC (INITIAL)	TOC (FINAL)	P_{TOT} (INITIAL)	P_{TOT} (FINAL)	P-BRAY 1 (INITIAL)	P-BRAY 1 (FINAL)
	G KG^{-1}		MG KG^{-1}			
WC	93.40 ± 6.82^{A}	90.51 ± 0.53^{A}	<0.01^{A}	<0.01^{A}	7.18 ± 0.08^{A}	7.44 ± 0.45^{A}
SS+WC	63.00 ± 0.87^{A}	53.17 ± 0.86*^{B}	132.06 ± 66.85^{B}	337.74 ± 17.88*^{A}	440.72 ± 22.79^{B}	550.08 ± 12.97*^{B}
SS+WC+EM	67.20 ± 1.29^{A}	59.04 ± 0.15*^{B}	65.30 ± 6.61^{B}	305.17 ± 6.35*^{A}	421.49 ± 49.41^{B}	497.96 ± 8.05*^{B}
SS+WC+E/W	68.50 ± 1.79^{A}	58.67 ± 0.99*^{B}	100.57 ± 37.58^{B}	386.18 ± 16.02*^{A}	422.89 ± 37.92^{B}	504.43 ± 31.04*^{C}
SS+WC+EM+E/W	79.30 ± 0.79^{A}	68.63 ± 1.06*^{B}	112.03 ± 15.65^{B}	286.25 ± 12.02*^{A}	369.40 ± 12.84^{B}	441.23 ± 20.91*^{C}
Process	**NH_4^+ (INITIAL)**	**NH_4^+ (FINAL)**	**NO_2^- (INITIAL)**	**NO_2^- (FINAL)**	**NO_3^- (INITIAL)**	**NO_3^- (FINAL)**
	MG KG^{-1}					
WC	0.74 ± 0.12^{A}	1.77 ± 0.46*^{A}	1.03 ± 0.24^{A}	0.91 ± 0.08^{A}	0.90 ± 0.32^{A}	6.52 ± 3.18*^{A}
SS+WC	278.46 ± 20.03^{B}	2.15 ± 0.49*^{B}	5.90 ± 0.75^{B}	9.16 ± 1.09*^{B}	8.06 ± 2.60^{B}	1327.93 ± 214.55*^{B}
SS+WC+EM	356.31 ± 47.68^{B}	2.00 ± 0.06*^{B}	6.10 ± 1.62^{B}	14.04 ± 0.98*^{B}	8.87 ± 2.82^{B}	1095.45 ± 81.69*^{B}
SS+WC+E/W	331.59 ± 32.45^{B}	24.62 ± 10.07*^{B}	4.76 ± 2.76^{B}	16.06 ± 0.24*^{B}	7.45 ± 5.63^{B}	2277.65 ± 125.08*^{C}
SS+WC+EM+E/W	220.80 ± 24.99^{B}	3.72 ± 1.24*^{B}	6.92 ± 0.18^{B}	12.21 ± 1.27*^{B}	10.06 ± 7.70^{B}	1479.29 ± 83.49*^{C}

^{a,b,c} means with the same letter were not significantly different ($P > 0.05$)
*Significantly different ($P < 0.05$) from initial content
TOC, total organic carbon; P-Bray 1, soil extractable P; SS, sewage sludge; WC, woodchips; EM, micro-organism inoculant; e/w, earthworm

Table 2 Heavy metal contents of earthworm body tissues before and after vermicomposting (n=9).

	Time (days)	Al (g.100 g^{-1})	As (µg.g^{-1})	Cu (µg.g^{-1})	Ni (µg.g^{-1})
SS+WC	0	9.50 ± 3.94^{a}	<0.05^{a}	84.95 ± 11.61^{a}	46.62 ± 4.22^{a}
SS+WC+EM	0	13.17 ± 4.58^{a}	<0.05^{a}	97.15 ± 3.99^{a}	50.87 ± 9.58^{a}
SS+WC	94	33.83 ± 17.20*^{b}	<0.05^{a}	147.55 ± 14.67^{*c}	89.97 ± 7.56^{*b}
SS+WC+EM	94	11.17 ± 5.46^{a}	<0.05^{a}	105.33 ± 20.29^{a}	51.00 ± 28.21^{a}

* Significantly different ($P < 0.05$) from initial content
^{a,b} Means with the same letter were not significantly different ($P > 0.05$)
SS – sewage sludge; WC – woodchips; EM – micro-organism inoculate

Table 3 List of the grass species mixture (per successional status group) sown in at the woodchip experiment sites at Impala Platinum Mine (Rustenburg), including the ratio of seed-mixture sown in per site (kg ha^{-1}).

Grass species name	Successional status	Kg ha^{-1}
Chloris virgata	Pioneer species	1
Cynodon dactylon	Pioneer species	4
Eleusine coracana	Pioneer species	1
Urochloa brachyura	Pioneer species	1
Enneapogon cenchroides	Pioneer/ Sub-climax species	2
Melinis repens	Pioneer/ Sub-climax species	1
Bothriochloa insculpta	Sub-climax species	2
Chloris gayana	Sub-climax species	1
Cenchrus ciliaris var. Gayndah	Sub-climax/ Climax species	2
Cenchrus ciliaris var. Molopo	Sub-climax/ Climax species	2
Eragrostis lehmanniana	Sub-climax/ Climax species	1
Panicum maximum	Sub-climax/ Climax species	3
Digitaria eriantha	Climax species	3
Total		24

VEGETATION ESTABLISHMENT ON PLATINUM TAILINGS DAMS

As mentioned, WC is a by-product of platinum mining and was already considered as an organic ameliorant (not composted or vermicomposted) during revegetation by Logan (1992). The primary reason for doing this was to improve the cation exchange capacity thereby lowering the base saturation and improving the adsorption of excess salts. Further, that WC could improve the physical properties of the growth medium by increasing its water holding capacity and stimulating biological activity, which is essential during revegetation strategies.

Most TDFs in South Africa are currently rehabilitated by vegetating them with grass. The promotion of a viable and sustainable vegetation cover at most of the mines is, however, a problem due to infertility and phytotoxicity of the growth medium. Early attempts to revegetate the TDFs at the investigated platinum mine were initiated utilising *Chloris gayana* (Rhodes grass), *Cenchrus ciliaris* (Buffalo Grass), *Eragrostis curvula* (Weeping Love Grass), *Cynodon dactylon* (Couch grass) and two legume species (Walmsley 1987) but no indication of species success was given. Little information is available to guide rehabilitation practices on platinum tailings, although this is a growing industry that has a considerable impact on land use. A unique concept investigated in this study was the use of VC as organic ameliorant during revegetation.

The objectives of this study were to determine the frequency and crown cover of the herbaceous (grass) species in the VC experimental sites as well as the establishment rate and success of the sown-in grass species.

The study area was divided between two the tailings dams at the mine which differed in age *viz.* tailings dam 1 (TDF1; non-operational and out of production since 1976) and tailings dam 2 (TDF2; operational). A total number of four sites were surveyed on TDF1, which included three experimental sites and one control site, while two sites were surveyed on TDF2, which included one experimental and one control site. The experimental sites on TDF1 were 30 m × 10 m in size and those on TDF2 30 m × 30 m. The control involved conventional chemical amelioration i.e. super phosphate (1200 kg ha^{-1}), $(NH_4)_2SO_4$ (350 kg ha^{-1}) and KCl (400 kg ha^{-1}). Sites were then treated with VC which was manually mixed into the soil to a depth of 30 cm. A total of 50 equivalents per ha per site (50 eq ha^{-1} site^{-1}) of VC were mixed into the soil.

After the addition of the VC to the site, a mixture of pre-mixed grass seed was sown in at each site which contained 12 different grass species (see **Table 3**) representative of all the successional status groups (e.g. pioneer and climax species, according to Van Oudtshoorn 1999). A total

Table 4 Summary of vegetation crown cover of the sites treated with vermicompost as remediation over a period of 2 years (Adapted from Rossouw 2005).

	Tailings Dam 1		Tailings Dam 2		
	Vermicompost	**Control**	**Vermicompost**	**Vermicompost**	**Control**
Vegetation cover (%)	64 ±0	30 ± 5.65	63.5 ± 12.02	59.5 ± 9.19	30.5 ± 10.61
Bare ground (%)	36 ±0	70 ± 5.65	36.5 ± 12.02	40.5 ± 9.19	69.5 ± 11.31

Fig. 1 Platinum mine tailings treated with inorganic fertilisers.

of 24 kg of grass seed mixture was sown-in per hectare (24 kg ha^{-1}) and no irrigation took place for the duration of the study. The only form of water supply available to the plants in these sites was rainfall with a total amount of 102 mm measured.

Vegetation cover for each site was determined by utilising twenty 1 m^2 quadrants at random locations within the sites. Coverage was then determined by measuring the ratio between the vegetation cover vs. bare ground (Kent and Coker 1997).

The estimated vegetation cover as observed in the study is summarised in **Table 4** and visual representations are presented in **Fig. 1** and **Fig. 2A–B**. The VC sites had the highest crown cover *viz.* 64:36, 63:37 and 59:41, respectively while those treated with inorganic fertilisers showed the lowest *viz.* 30:70 and 31:69.

Plant species, which contributed to the highest degree of crown cover on the VC treated sites included the perennial species *C. ciliaris* (L.) var. Molopo and Gayndah, *C. gayana* Kunth, *Melinis repens* (Willd) Zizka and the stoloniferous species *C. dactylon* (L.) Pers., *Digitaria eriantha* Steud. All of these were part of the sown seed and therefore indicate a successful state of rehabilitation on the VC sites.

Based on the results, the following conclusions can be made in general regarding the success of the VC rehabilitation practices at the investigated platinum mine. The high frequency of both annual and perennial grass species indicates that the rehabilitation at the VC sites can be regarded as successful based on the different stable vegetation components (Kent and Coker 1997). These plants in the VC sites also have a high ecological status (Van Oudtshoorn 1999) which indicate that the vegetation in the rehabilitated areas is in a good condition. There is also a high state of ecological stability notable in all the rehabilitated sites, based the high diversity of the different vegetation types. Further, the occurrence of annual and pioneer plant species (grasses and forbs) in the VC sites contribute to the enrichment of the soil and serves as a source of organic material and increases the available soil nutrients. This will favour the establishment and growth of perennial and climax grass species in the long-term process of succession. Based on this it can therefore be concluded that the addition of the woodchip-VC mixture to the TDFs proved to be a very successful part of rehabilitation at platinum mines.

Fig. 3 Construction of mini dumpsites examined and layout of plots during the field trials.

VEGETATION ESTABLISHMENT ON DIAMOND TAILINGS DAMS

The objectives of this study were to determine the type and optimum concentration of VC in conjunction with chemical amelioration and different seed mixes for vegetation establishment using constructed mini dump sites (**Fig. 3**). This was achieved by using plant photosynthesis (chlorophyll a

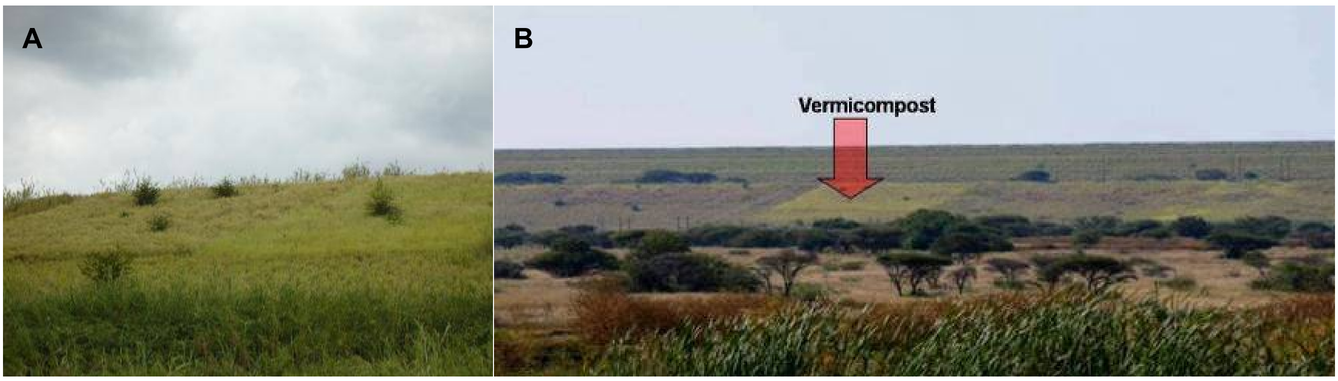

Fig. 2 (**A**) Platinum mine tailings treated with woodchip-vermicompost. (**B**) Platinum mine tailings treated with woodchip-vermicompost.

Table 5 Layout of the different treatment groups evaluated for the duration of the study.

Treatment	n	Vermicompost (tons ha^{-1})	Chemical amelioration (a or b)*	Seed mix (1 or 2)#
Control 1	4	90	-	-
Control 2	4	60	-	-
A (90a1)	2	90	A	1
B (90b1)	2	90	B	1
C (90a2)	2	90	A	2
D (90b2)	2	90	B	2
E (60a1)	2	60	A	1
F (60b1)	2	60	B	1
G (60a2)	2	60	A	2
H (60b2)	2	60	B	2

*Fertiliser treatment A: KNO, 3:1:5 Cl-free and Super phosphate (625 kg ha^{-1}).
*Fertiliser treatment B: $CaNO_3$ (25 kg ha^{-1}) and $MgNO_3$ (12.5 kg ha^{-1})
#Seed mix 1: *Enneapogon cechroides*, *Melinis repens*, *Chloris virgata*, *Urochloa brachyura*, *Eleusine coracana*, *Cenchrus cilliaris* var. *Molopo*, *Cenchrus cilliaris* var. *Gayndah*, *Eragrostis lehmanniana*, *Panicum maximum*, *Digitaria eriantha*, *Cynodon dactylon*, *Chloris gayana*, *Bothriochloa insculpta*.
Seed mix 2: *Enneapogon cechroides*, *Melinis repens*, *Chloris virgata*, *Tragus berteronianus*, *Aristida congesta*, *Cenchrus cilliaris* var. *Molopo*, *Cenchrus cilliaris* var. *Gayndah*, *Eragrostis lehmanniana*, *Schmidtia pappophoroides*, *Fingerhuthia africana*, *Eragrostis echinochloidea*, *Cynodon dactylon*, *Chloris gayana*

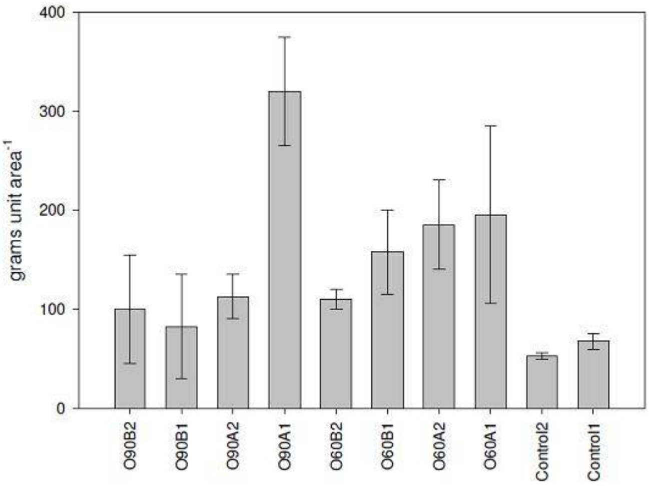

Fig. 4 Plant biomass in the different treatment plots (g/quadrant).

fluorescence) and plant biomass as measured endpoints. The different treatment groups are summarised in **Table 5**. Another objective was to identify and recommend suitable grass species to be utilised during the rehabilitation process by quantitatively rating the establishment success of the seeded species.

The use of chlorophyll a fluorescence is based on the fact that certain environmental influences can cause fluctuations in the photosynthetic levels of plants and has been used as a screening tool for stress tolerance and photochemical reaction to stress (Van Heerden *et al*. 2004). The method is based on the registration of light emitted by photosystem II (PS II), and is amongst the most perspective biophysical methods to evaluate the physiological state of plants (Goltsev *et al*. 2003). The use of chlorophyll fluorescence on intact, attached leaves has proved to be a reliable, nonintrusive method for monitoring photosynthetic events and judging the physiological status of the plant (Kocheva *et al*. 2004).

Plant biomass was collected by cutting plant material 5 cm above the ground with sheers and air drying the material at 60°C for 48 hrs after which it weighed. In addition, a subjective rating of the crown cover, vitality, individual plant biomass and species composition was made for every plot.

The vegetation biomass of the plots are summarised in **Fig. 4**. The highest plant biomass was found in site 90A1,

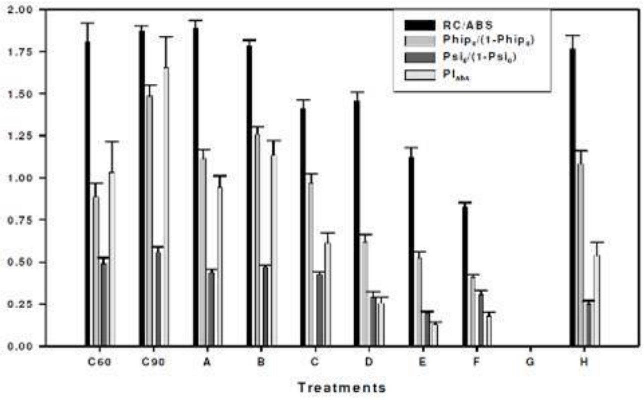

Fig. 5 Statistical representation of performance index in grass leaves.

but generally higher biomass was found among the plots treated with 60 ton ha^{-1} VC. In general the values for plant biomass were found in the sites treated with fertiliser type A (KNO and Super phosphate). The two control sites had the lowest biomass values compared to all the other treatments but had the same species diversity and frequencies as the other sites. This could be an indication that the VC application used in this case could be the reason for higher biomass.

C. ciliaris (perennial) and *C. dactylon* (perennial, creeping grass) were the dominant species and most were in the reproductive stage with numerous seeds visible between the plants on the soil surface. This indicates that seed production is taking place and that the grass species could occur in higher densities in these sites in future within this protective environment. It is, therefore, possible for the plants to successfully establish, should enough moisture be available and that the extent of competition not be too high i.e. between the different species within the different successsional stage groups. This was corroborated by the occurrence of small seedlings of species such as *C. virgata* in many of the sites indicating an increased and successful establishment of young seedlings. All three the plant phenological stages (seedlings, vegetative and reproductive) of growth were present in the sites, which indicate successful establishment of sown-in species and the possibility of succession in future indicating successful rehabilitation strategies.

Fluorescence measurements were done in the dark after at least 2 hrs of darkness. The fluorescence induction curves were measured with a plant efficiency analyser (PEA, Hansatech Instruments Ltd, King's Lynn, Norfolk, UK) and recorded for 1 sec (Van Heerden *et al*. 2004). Each Chlorophyll *a* fluorescence induction curve was analysed according to the JIP-test (so named on the basis that the different steps of the fluorescence transient are labelled alphabetically, as O, J, I, P) which is described in detail by Strasser and Strasser (1995).

Not all the treatments sites (A1-D6) offered suitable material for fluorescence measurements. However, since the measurements were done during June (a relatively dry period and the onset of winter) not enough data was gathered (**Fig. 5**) to determine any important physiological differences. Fluorescence measurements were carried out for some treatment sites. All the measurements involved measuring fluorescence for the same species (*Cenchrus ciliaris*) in all the sites, except for one (*C. dactylon*). Values for the performance index were considerably low as a result of the winter period where most of the grasses finished an annual cycle. The low performance index values could also be as a result of some water stress in the extensively dry region of the Northern Cape, however water stress significantly reduces carbon dioxide assimilation rate and leaf stomatal conductance and not photosynthesis directly (Lu and Zang 1998). Osmotic stress also causes rapid dehydration but the photosystems retain their efficiency, and this kind of stress also causes severe injury to the plant cell

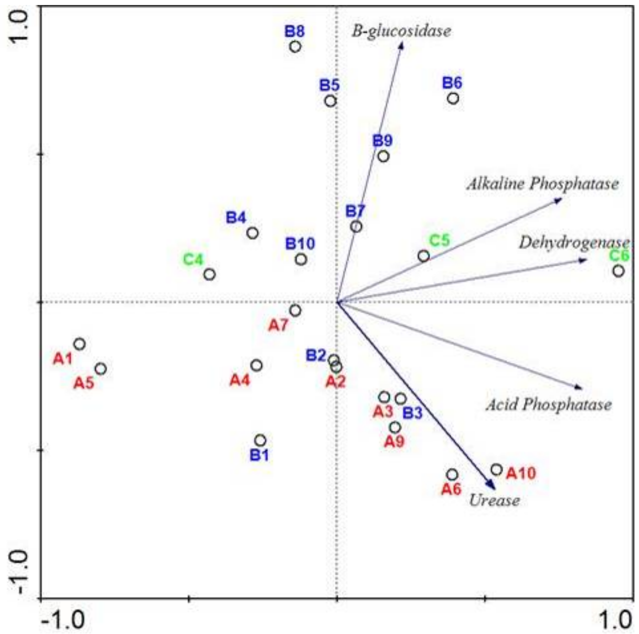

Fig. 6 Principal Component Analysis ordination diagram of the potential microbial enzymatic activities as observed for the different treatments.

membranes (Kocheva *et al*. 2004). Thus, very small differences make it difficult to draw any conclusions.

Although no significant results were obtained during this part of the study, the use of plant physiological activity as indicator of revegetation success shows some promise as a potential evaluation tool in determining the success of revegetation strategies.

VEGETATION ESTABLISHMENT ON IRON ORE TAILINGS DAMS

As in the previous studies, the objective of this investigation was to assess the success of VC as ameliorant on iron ore TDFs utilising vegetation cover and soil microbial activity (**Fig. 6**). Visual representations of the rehabilitation success utilising VC is represented in **Fig. 7A–C**. The results of this study is summarised in a technical report by Van Rensburg and Roussouw (2008). The major findings of this study included the fact that the addition of VC to the TDFs plays an important role in with regards to microbial activity which is an important component of the soil development process in post mining rehabilitation (Šantrůčková *et al.* 2004). Dehydrogenase activity gave an indication of microbial activity whereas β-glucosidase activity gave an indication of cycling of organic matter in the soil system. It was also found that in the case of iron ore TDFs the addition of a layer of topsoil in addition to VC treatment gave good results.

CONCLUSIONS

Based on the laboratory studies it was ascertained that the vermicomposting of WC with the addition of an inoculate was prescribed for large-scale field studies. When utilising vegetation cover as an endpoint for rehabilitation success on TDs it was found that VC was superior to chemical ameliorants. This under natural conditions with no irrigation; which is important since South Africa is a semi-arid country. It was also indicated that the rehabilitation strategy was successful. Evaluation of the optimum concentrations of VC together with chemical amelioration utilising crown cover and plant physiology as indicators did not produce conclusive results. More tests are needed to corroborate these. The investigation with regards to woodchip VC as ameliorant on iron ore tailings revealed that mixing it with the topsoil gave the best results. This was based on utilising microbial enzymatic activities as endpoint. From the studies presented it is clear that vermicomposting of organic waste WC was feasible on a large-scale. Further, that its use in different rehabilitation strategies at different mines yielded positive results. This was even the case when using different endpoints to evaluate the rehabilitation success.

In order to achieve the above-mentioned vegetation success the application of the equivalent of 150 tons of organic material (not for its nutritional properties but for increasing the water-holding capacity as well as bacterial activity within the growing medium) per hectare is vital since disturbed areas pose extreme conditions for vegetation colonisation and survival. Not only soil chemical limitations e.g. soil nutrient deficiencies, high salt concentrations and pH extremes inhibit sustainable rehabilitation, but primarily soil physical traits contribute to the failure of plant succession. These include poor soil moisture retention, high bulk densities, and especially a lack of "safe sites". Safe-site estab-

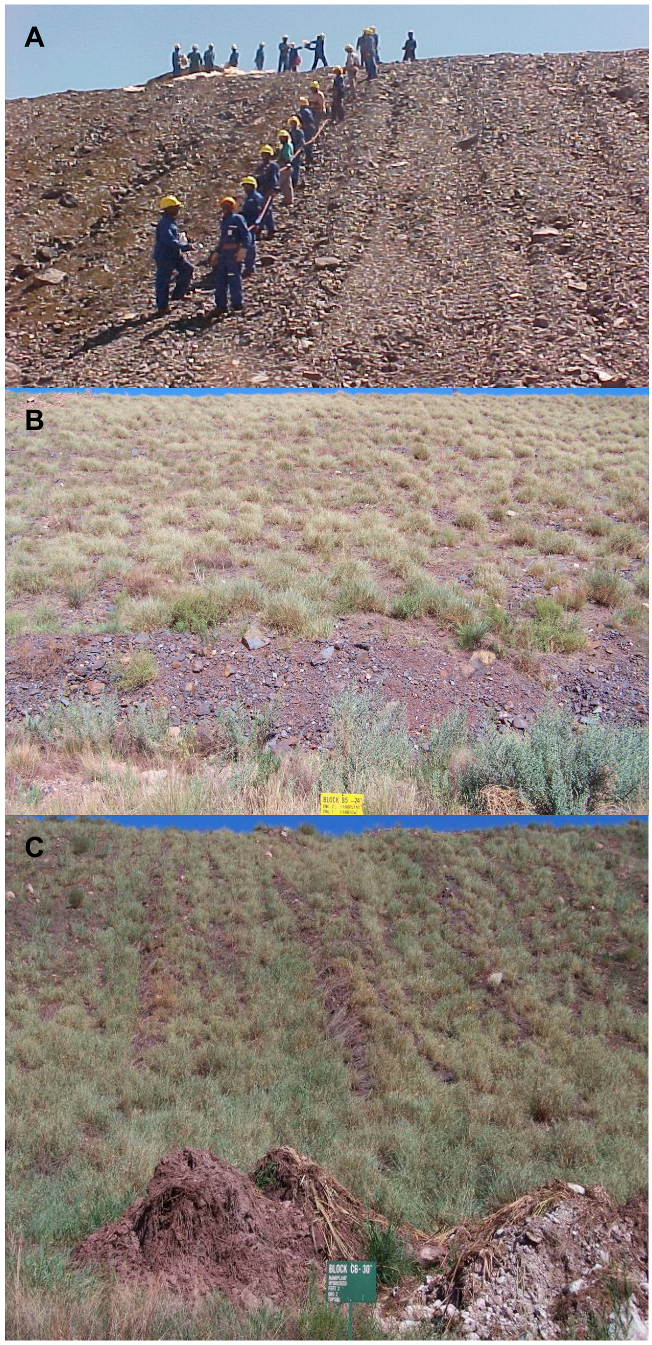

Fig. 7 (**A**) Untreated iron ore mine tailings. (**B**) Iron ore TDF with added organic matter and fertilizer with no topsoil indicated less dense vegetation. (**C**) Iron ore TDF with added topsoil, organic matter and fertilizer indicating a denser establishment of vegetation cover.

lishment is crucial for plant successionary processes and is the basis for self-sustainable rehabilitation. The most efficient way to establish safe-sites is through the addition of organic matter in the form of good quality VC. Although there is a direct correlation between soil organic matter and rehabilitation success the importance of the soil carbon fraction in rehabilitated soils is one of the most undervalued components in rehabilitation. Through our rehabilitation experience, it is clear that one of the main limitations of tailings materials in terms of vegetation sustenance is the lack of organic matter in the growth medium profile. It is really the presence of this organic component in the soil that bio-activate the largely sterile material and optimize microbial growth, biochemical balances in the soil and the acceleration of soil profile development. The organic material also have high moisture retention capacity, which sees the vegetation through dry periods, and furthers safe-site establishment, optimising natural succession that leads to more sustainable vegetation cover. Through intensive experimentation we found that root development, above-ground biomass production, and therefore basal and crown cover, outperformed all the areas without compost. The VC treated areas also had exceptionally high biodiversity compared to the untreated sites and its usage ideally fills this invincible requirement of self-sustaining soil functioning.

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