Ecological Engineering 37 (2011) 504–510

Contents lists available at ScienceDirect

Ecological Engineering

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

Standardizing rehabilitation protocol using vegetation cover for bauxite waste (red mud) in eastern India

Suresh Chauhan*, Anirban Ganguly[1]

TERI, India Habitat Center, Lodhi Road, New Delhi, India

ARTICLE INFO

Article history:
Received 22 April 2010
Received in revised form
24 November 2010
Accepted 12 December 2010
Available online 21 January 2011

Keywords:
Aluminum
Gypsum
Red mud
Rehabilitation
Vermicompost

ABSTRACT

This paper presents results of a research trial for standardizing a rehabilitation protocol through developing vegetation cover to rehabilitate red mud ponds. The trial was conducted at one of the red mud ponds of Hindustan Aluminum Company Limited (HINDALCO), the largest aluminum producer of India, at Ranchi district of Jharkhand State in eastern India. The trial was set up as a factorial experiment with five tree species, four treatment combinations, two irrigation types and two pit sizes. Growth data of five tree species for six parameters (collar diameter, GBH, plant height, crown diameter, number of leaves and number of branches) were recorded over 19 months. Four-way independent ANOVA was conducted on the growth data where all main effects, interaction effects and marginal means were computed. A best fit plantation protocol was developed out of this analysis, with *Acacia nilotica* and *Albizia lebbeck* emerging as the best performing tree species. Among different treatments, 20% gypsum along with 10% vermicompost and acid producing bacteria emerged as most preferred treatment amenders. Between two irrigation types, drip irrigation provided better growth results in all the tree species. Effect of the pit size was not found to be statistically significant for this time scale.

1. Introduction

Aluminum, the third most abundant element after oxygen and silicon, never occurs naturally in its pure form in the earth's crust. Around 8% of the earth's crust is composed of aluminum, usually found in oxide form, known as bauxite. Bauxite is composed of monohydrate and trihydrate forms of alumina in various proportions. The amount of bauxite residue produced during the refining process is significant and depends on the quality of the used bauxite mineral. Approximately 1 ton of alumina produces 1.5–2 ton of dry bauxite residues, commonly known as "Red mud". The most common method for red mud disposal is storage in impounded dike deposits adjacent to the alumina processing plants (Krishna et al., 2005). Globally, it has been estimated that around 70 million metric dry ton of red mud was produced annually during the extraction of alumina from bauxite ore through Bayer Process (Courtney et al., 2009).

The liquid phase of red mud contains significant concentration of caustics, sodium aluminates and sodium carbonate, which are highly alkaline in nature and causes dispersion of the particles resulting in poor aeration and low water availability. The red mud is pumped from the plant as slurry and generally stacked in pits called "Red mud Pond". Due to low infiltration, poor hydraulic conductivity, difficult moisture movement characteristics and poor microbial activity, the physical condition of the red mud pond hinders tillage operation, seed germination and root proliferation (Chauhan et al., 2006).

During the dry season, the surface of the red mud pond becomes very hard and develops cracks of reticular design due to swelling/shrinking of its finer fractions. In the wet season it becomes sticky, forms clods and gets a crust on drying. Unamended bare bauxite residue displays alkaline, sodic properties with minimal inherent nutrient content and poor soil structure, and thus can limit soil biological properties (Courtney et al., 2010). Due to the hazardous nature, restoring ecological values and vegetation cover in a cost-effective and sustainable manner is a serious challenge to alumina producers worldwide (Gherardi and Rengel, 2001). There have been few attempts in the past to rehabilitate the red mud residue deposits and bauxite mines wastes by establishing vegetation cover (Wong and Ho, 1994), but ecological succession has been demonstrated on metalliferous mine tailings (Chauhan and Silori, 2010; Skousen et al., 1994; Schaaf, 2001; O'Neill et al., 1998; Bagattto and Shorthouse, 1999; Shu et al., 2005) and alkaline wastes (Lee and Greenwood, 1976; Ash et al., 1994). It has been done in rare successful cases; however, the nutrient concentrations in veg-

* Corresponding author. Tel.: +91 11 24682100.
E-mail addresses: sureshc@teri.res.in (S. Chauhan), anirban@teri.res.in (A. Ganguly).
[1] Tel.: +91 11 24682100.

0925-8574/$ – see front matter
doi:10.1016/j.ecoleng.2010.12.017

etation tend to be low, which can be improved to some extent by addition of ameliorants such as gypsum and sewage sludge (Barrow, 1982; Wong and Ho, 1991).

Aluminum production in India has grown since its beginning in 1938. The annual production target set by the Ministry of Mines, Government of India, in 2007–2008 was 1237 kt. Due to growing demands in the construction, electrical, automobile and packaging industry, production is expected to increase over the years ahead. The aluminum industry in India is highly concentrated with relatively few players dominating the market. Hindustan Aluminum Company Ltd. (HINDALCO) is the largest among them, controlling about 40% of market share. The Muri aluminum refinery (in Jharkhand State of eastern India) is one of HINDALCO's major brownfield projects with a recent capacity expansion from 110 to 450 ktpa.

The present research trial was initiated with a view to standardizing rehabilitation protocol and improving physicochemical properties of red mud pond. The vegetation trials were carried out in various soil amenders, irrigation types and pit sizes with suitable tree and grass species at one of the red mud ponds of HINDALCO, located at Muri.

2. Study area

The experiment site of 2 ha area is located at red mud pond number 2 of HINDALCO, at Muri, Ranchi, Jharkhand. Muri is a small town situated at 23°22′43 "North Latitude and 85°52′25" East Longitude at an average elevation of 260 m above mean sea level, which is almost 70 km away from the state capital, Ranchi, and 4 km from the block headquarter Silli. Topographically, the research site is in the plain terrain with small hillocks. The climate of the region is semi-arid to tropical and temperature varies from 9.7 °C during December to 38.4 °C during May. The average annual rainfall in the region is about 1452.7 mm and average relative humidity ranges from 28% to 86%. The winds in the region are light to moderate and the predominant wind direction is northwest followed by south.

3. Method

The research trial was carried out at Muri in the month of February 2007 and continued until May 2009. Based on the rehabilitation research studies on red mud and restoration work experiences, afforestation techniques on red mud pond were developed by testing physico-chemical properties of red mud, selecting suitable tree and grass species, choosing optimal combination of soil amenders such as gypsum and vermicompost, besides biological inoculums that are best suited for raising vegetation cover on substrate of red mud pond. The rehabilitation research trials comprised various combinations of species mix, soil amenders, irrigation requirements and pit sizes. The selection of tree and grass species was driven by some of their favorable properties such as high tolerance of alkaline and saline soils, relatively fast growth rates, soil-binding properties, and ability to supply biomass to local people in the form of fuel wood and fodder (Sharma et al., 2004a). Gypsum and vermicompost were used as additive materials in the red mud, which provide nutrients to plants and act as soil conditioners to improve certain physiochemical properties of red mud. However, emphasis has been given first to build up soil organic matter, nutrients and vegetation cover to accelerate natural recovery process in the red mud. The phases of the research trial were as follows:

i. Pre-afforestation
ii. Experiment design
iii. Afforestation
iv. Statistical analysis of growth data

3.1. Pre afforestation

3.1.1. Physico-chemical analysis of red mud

Red mud samples were taken from four different depths, i.e., 15 cm, 30 cm, 45 cm and 100 cm at various places of red mud pond no. 2. These samples were mixed together to form a uniform mixture on the basis of different depths. Thus, only four samples, one each from 15 cm, 30 cm, 45 cm and 100 cm depth were analysed separately before taking up the afforestation activity in the month of April 2007. These samples were analysed to assess the changes in physical and chemical characteristics of the red mud, which determine the growth parameters.

3.1.2. Selection of tree and grass species

Five native tree species namely *Terminalia arjuna* (Arjun), *Acacia nilotica* (Babool), *Pongamia pinnata* (Pongamia), *Bauhinia variegata* (Kachnar) and *Albizia lebbeck* (Kala Siris) were selected on the basis of their timber, fuel wood and fodder values, besides high tolerance to the saline and alkaline soil and existing adaptability to the edaphic and climatic condition of the local area. These selected tree species are fast growing, capable of producing a prolific deep root system and can thrive well under the moisture stress condition. Seeds were procured and saplings were raised at the nearby Forest Department nursery in the month of February 2007, almost six months prior to taking up the plantation. Besides, based on highly saline and alkaline tolerance and capability to control soil erosion through their proliferated root system, two grass species namely *Pennisetum pedicellatum* (Dinanath grass) and *Stylosanthes hamata* (Stylo hamata) were selected for the research trials. During the month of March 2007, 10 kg of quality seeds of *P. pedicellatum* and 12 kg of quality seeds of *S. hamata* were procured from Indian Grassland and Fodder Research Institute (IGFRI), Jhansi.

3.2. Experiment design

The experiment was set up as a factorial design. The design was of the following form: five tree species (*T. arjuna, A. nilotica, P. pinnata, B. variegata* and *A. lebbeck*)*four treatment combinations (10% vermicompost + red mud (control) – C_0, 10% gypsum + 10% vermicompost + red mud + bacteria – C_1, 15% gypsum + 10% vermicompost + red mud + bacteria – C_2, and 20% gypsum + 10% vermicompost + red mud + bacteria – C_3)*two irrigation types (Drip irrigation and Hand watering)*two pit types (normal pit and pit with augur hole), resulting in 80 factor combinations. With three replicates for each combination and measurements on two trees per replicate, a total of 480 data points were available against six dependent variables (growth parameters) namely collar diameter, GBH (Girth at Breast Height) plant height, crown diameter, number of leaves, and number of branches. The basic feature of this design was that each of the independent variables (predictors)—species, treatment, irrigation type and pit type were measured using different experimental participants. For all the variables, the average monthly change over the period under experiment was considered. In cases of all the variables, this period was of 19 months (September 2007 to March 2009), except in the case of GBH, where the observations were taken over a shorter period.

3.3. Afforestation

The experimental site of red mud pond was first tilled and then leveled during the month of April 2007. Thereafter, the entire site was completely fenced to protect the young plantation from cattle and human interference. The pit digging work was started after completing the fencing work in the month of May and completed in June 2007. Two types of pits were dug in two equal halves of the entire 2 ha experimental plot. The first type was of normal pit with augur of size 45 cm × 45 cm × 90 cm and the second type was normal pit without augur of 45 cm × 45 cm × 45 cm size. The plant to plant and row to row spacing was 3 m × 3 m. For preparing the different treatment combinations, around 25 ton of gypsum, 20 ton of vermicompost and 20 kg of nitrogen fixer and acid producing bacteria were applied inside the pits of experimental site.

The plantation was initiated by end of July and completed by middle of August 2007. All the saplings of selected five tree species were planted as per the detailed layout of experimental design. The experimental site comprised of four sub plots, with each sub plot having a total of 360 saplings, 72 saplings of each of the five species. Thus, a total of 1440 saplings were planted in the entire experiment site. Different treatment combinations along with gypsum, vermicompost and bacterial inoculums were prepared and applied in the pit during planting tree species in the entire experimental site. The seed sowing of the grass species was done just after completion of the tree plantation. The seeds of both the grass species were sown alternately between the two plantation rows, leaving open the third row for monitoring path. This was done to ensure that if one species was unable to show good growth, the next would dominate it. Both grass species would not only check run off and wind erosion of surface cover, but also can improve the physico-chemical properties of red mud by adding organic matter through carbonation reactions. Drip irrigation was installed in one-half of the research plot during mid-August 2007, just after completion of the plantation activities. Saplings of the other half of the experimental site were watered manually. The drip irrigation system ensured continuous and sufficient supply of water for shallow root system to be developed on such an inhospitable site and soil environment. Around 5–8 l of water per sapling per day was provided through the drip irrigation system against 8–10 l per sapling per day in case of hand watering, however this frequency reduced during the monsoon. This helped to minimize leaching of nutrients and loss of water from pits. The objective of the installing drip system was twofold, to conserve the water and to assess the impact of using controlled irrigation to the saplings and compare the growth parameters against the saplings being raised by using hand watering under different treatments in the second half of experimental site. Silvicultural operations such as weeding, hoeing, application of pesticides and insecticides were uniformly carried out continuously throughout the project duration in order to achieve healthy growth and better survival of the plants.

3.4. Statistical analysis of growth data

Data on growth parameters of tree and grass species were collected from September 2007 to March 2009. In a factorial design, the independent variables are measured against several dependant variables (factors) that are in the nature of discrete categories. A factorial design is said to be independent when the experimental participants (the individual trees) are all different. This is distinguished from a related factorial design where the same participants are used for repeated observations. In the present case, an independent factorial design is used with four independent variables – species (5), treatments (4), irrigation type (2) and pit type (2) – against six growth parameters. We conducted four-way independent ANOVA to obtain the basic results. The steps in the analysis were as follows:

a. Computation of the 'main effects', that is, the measure of the variance in the dependent variables due to (explained by) each independent variable, ignoring the effects of the other variables.
b. Computation of the 'interaction effects', that is, the measure of variance due to (explained by) the interaction of each possible combination of two, three or four variables.
c. Computation of marginal means for each level of each factor to compare the growth performance across six growth parameters. (The marginal means are means of growth parameters for each factor averaged over the levels of the other factors.)

A 5% level of significance is used for all statistical procedures. All data have been analysed using the General Linear Model (GLM) in SPSS Version 16.

4. Results

4.1. Change in physico-chemical analysis of red mud

At the end of the project in March 2009, changes were noted in the soil characteristics. The pH and electrical conductivity showed a decline values at all levels of depth. The treatment resulted in a decrease in alkalinity with post-treatment pH values in the range of 7.60–8.20. The decline in pH was most discernable at 15 cm depth, while the decline at greater depths was observed to be marginal. Overall available sodium declined by 6%, while organic carbon increased by 16%. Also, available Nitrogen, Phosphorus and Potassium increased by 105%, 52% and 8% respectively. The cation exchange capacity exhibited low values (average 0.54 mequiv./100 g) at pre-treatment level but increased

Table 1
Change in the characteristics of red mud.

Parameters	Results in different depths				Units
	15 cm	30 cm	45 cm	100 cm	
pH value (1:5) at 25 °C	8.18 (7.60)	8.17 (8.16)	8.21 (8.20)	8.19 (8.20)	
Electronic conductivity (1:5) at 25 °C	424.0 (362)	330.0 (370)	381.0 (380)	356.0 (350)	µs/cm
Exchangeable sodium	9.21 (8.15)	10.90 (10.74)	11.50 (11.13)	13.19 (12.10)	mequiv./100 g
Organic carbon	1.60 (1.75)	0.92 (1.59)	1.4 (1.58)	1.7 (1.63)	%
Available sulphur	Not detectable (0.1)	Not detectable (0.5)	Not detectable (0.09)	Not detectable (0.09)	%
Available nitrogen (NO_3)	99.0 (212)	73.60 (190)	115.56 (215)	125.3 (229)	kg/ha
Available phosphorus (P_2O_5)	179.9 (93)	140.76 (109)	179.29 (343)	130.86 (413)	kg/ha
Available potassium	0.61 (0.81)	0.71 (0.75)	1.23 (1.27)	1.32 (1.35)	mequiv./100 g
Cation exchange capacity	0.40 (5.08)	0.46 (5.85)	0.79 (7.87)	0.53 (8.87)	mequiv./100 g
Soil texture					
Sand content	33.16 (35.34)	28.42 (31.04)	29.02 (31.06)	30.81 (35.13)	%
Clay content	19.49 (20)	14.0 (23.03)	28.58 (29.5)	25.18 (23.59)	%
Silt content	47.35 (44.66)	57.58 (45.03)	42.40 (39.43)	44.01 (41.28)	%

*Values within brackets were analysed at the end of the project.

Table 2
Main effect—species.

Variable	Sum of squares	Mean square	*F*	Sig.
Collar diameter	2.034	0.508	171.367	0.000
Girth at breast height	3.853	0.963	49.161	0.000
Height	10666.414	2666.603	398.911	0.000
Crown diameter	5236.449	1309.112	164.009	0.000
Leaves	1144627.062	286156.765	404.222	0.000
Branches	673.081	168.270	514.740	0.000

Degrees of freedom = 4.
Type III sum of squares have been calculated for height, collar diameter, leaves and branches and Type IV sum of squares have been calculated for crown diameter and GBH (due to the presence of missing values).

Table 3
Main effect—treatments.

Variable	Sum of squares	Mean square	*F*	Sig
Collar diameter	0.087	0.029	9.780	0.000
Girth at breast height	0.053	0.018	0.907	0.438
Height	100.137	33.379	4.993	0.002
Crown diameter	121.701	40.567	5.082	0.002
Leaves	16327.976	5442.659	7.688	0.000
Branches	1.304	0.435	1.329	0.264

Degrees of freedom = 3.

considerably after the treatment (average 6.92 mequiv./100 g). The magnitude of this capacity is known to be a determinant of the level of soil fertility since the 'exchange material' acts as a storehouse in which nutrient ions have been known to be preserved in a form available to plants (Wild et al., 1979). This indicated overall improvement in the physico-chemical properties of the red mud (Table 1). These changes affected growth outcomes positively as the following sections show. The growth outcomes were captured in terms of six growth parameters mentioned earlier.

4.1.1. The main effects

The main effects determine the statistical significance of each of the independent variables in determining the outcome, when considered in isolation. The main effects for species and treatment are presented in Tables 2 and 3. The effect was significant for all the parameters indicating that growth rates are affected by choice of species. In case of treatment, the main effect was significant for four of the six parameters. The main effect for irrigation was significant for all parameters except GBH (Table 4). For pit type, the effects were significant for only three parameters—leaves, branches and crown diameter. This provided a basis to effect a reduction in factors for the next stage. We considered treatment type, species and irrigation type while developing the best combination set, leaving out pit size. We however do not imply that pit size has no effect on growth, but we observe that the effect is not significant for half of the parameters at this time scale. It is expected that over a longer duration as the roots develop, the pit size will have a significant effect.

Table 4
Main effect—irrigation.

Variable	Sum of squares	Mean square	*F*	Sig
Collar diameter	0.438	0.438	147.746	0.000
Girth at breast height	0.069	0.069	3.502	0.062
Height	1177.961	1177.961	176.217	0.000
Crown diameter	1115.543	1115.543	139.758	0.000
Leaves	376031.274	376031.274	531.178	0.000
Branches	58.485	58.485	178.907	0.000

Degree of freedom = 1 (sum of squares = mean square).

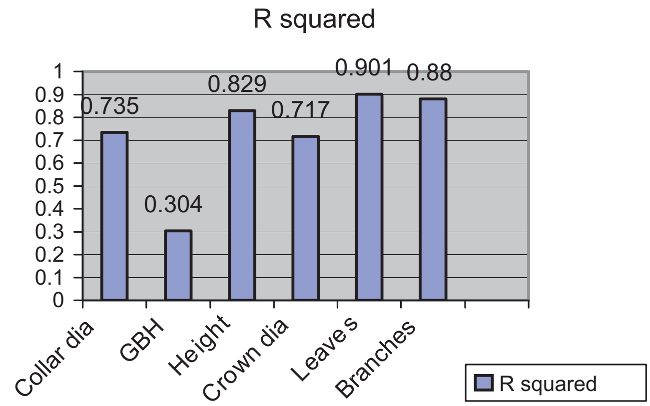

Fig. 1. Coefficient of determination.

4.1.2. Interaction effects

In the present design, we can have 6 two-way interactions, 3 three-way interactions and 1 four-way interaction. The interaction effects showed an interesting pattern. The treatment interaction effects with irrigation and pit size were not significant except in one case, whereas the species-treatment interaction was significant for three of the six variables. In general, three-way and four-way interactions were significant in less number of cases as compared to two-way interactions. A notable exception is the treatment—species–irrigation interaction, which showed significant results in four of the six variables (Table 5). Loss of significance in higher order interactions would imply that not all factors work in combination to achieve the growth outcomes; hence a 'perfect combination' of all desirable factors was not anticipated in this study.

4.1.3. Substantive importance of the factors and variability

Substantive importance of the factors (independent variables) was captured through the coefficient of determination – R^2. The highest R^2 value was returned by leaves and the lowest by GBH. The low R^2 value for GBH can be partly attributed to the fact that the changes were measured in this case over a relatively shorter period and the substantive importance of GBH growth may go up as observations over longer durations are taken (Fig. 1).

The coefficient of variation (CV) was highest in case of branches (0.84) and lowest in case of collar diameter (0.23) when compared across species. The CV was highest for leaves (0.11) and lowest for branches (0.05) when compared across treatment levels. It is clear that the CV values when compared across species are consistently higher than those when compared across treatments (Fig. 2).

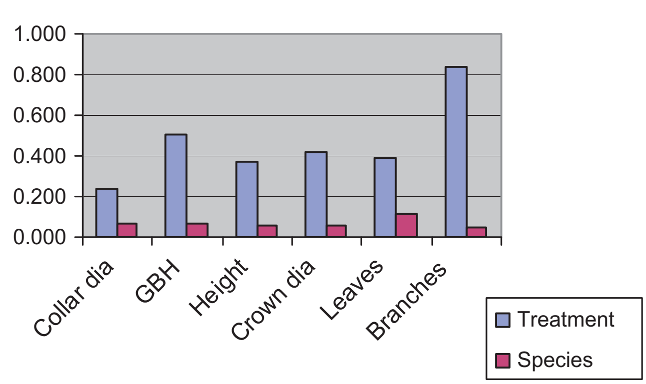

Fig. 2. Coefficient of variation of marginal means across treatment types and species.

Table 5
Interaction effect (significance values – *p*).

Interactions	Collar dia.	GBH	Height	Crown dia.	Leaves	Branches	Number of interactions sig
S*T	0.095*	0.995	0.969	0.095	0.000*	0.007*	3
S*I	0.000*	0.584	0.000*	0.768	0.000*	0.000*	4
S*P	0.379	0.022*	0.003*	0.008*	0.000*	0.000*	5
T*I	0.488	0.237	0.257	0.000*	0.077	0.376	1
T*P	0.641	0.124	0.718	0.000*	0.115	0.771	1
I*P	0.010*	0.163	0.002*	0.268	0.000*	0.006*	4
T*S*I	0.000*	0.963	0.002*	0.209	0.000*	0.000*	4
T*S*P	0.020*	0.017*	0.108	0.209	0.210	0.938	2
S*I*P	0.554	0.523	0.810	0.168	0.000*	0.000*	2
T*I*P	0.000*	0.853	0.644	0.329	0.073	0.589	1
S*T*I*P	0.241	0.046	0.102	0.032*	0.520	0.493	1

S: species; T: treatments; I: irrigation types; P: pit types.
* The result is significant ($p < 0.05$).

Table 6
Marginal means for species (average growth/month).

Species	Collar dia. (cm)	GBH (cm)	Height (cm)	Crown dia. (cm)	Leaves (no.)	Branches (no.)
Terminalia arjuna	0.184	0.053	6.226	6.913	28.290	0.957
Acacia nilotica	0.281	0.296*	12.625	13.146*	151.342*	3.374*
Pongamia pinnata	0.180	0.074	6.572	5.430	24.942	0.567
Bauhinia variegata	0.187	0.076	6.991	6.032	23.235	0.793
Albizia lebbeck	0.341*	0.155	18.339*	12.442	49.572	−0.101

* The highest value.

4.1.4. Marginal means

We obtained marginal means for treatment, species and irrigation type. Pit type was retained as an input variable while determining marginal means, but marginal means for pit size itself were not computed since its effects are not statistically significant. Marginal means denote the mean values corresponding to one factor averaged over various levels of the other factor(s). In case of species, for example, the values are averaged over the levels of treatment, irrigation and pit size. In four (branches, crown diameter, GBH and leaves) out of six variables, *A. nilotica* recorded the maximum growth while for the remaining two variables, *A. lebbeck* showed the best performance. *A. lebbeck* recorded the maximum increase in height and *T. arjuna* the lowest increase. *A. lebbeck* recorded maximum increase in collar diameter and *P. pinnata* the lowest increase. For crown diameter, *A. nilotica* recorded the maximum increase and *P. pinnata* the lowest increase. For GBH, branches and leaves, *A. nilotica* performed the best. For these three parameters, *T. arjuna*, *A. lebbeck* and *B. variegata* respectively showed least growth (Table 6). Among the various treatments, the results indicated that for four (collar diameter, crown diameter, GBH and leaves) out of six variables, treatment C3 showed the best results. For height and branches, treatments C2 and C1 showed the best results respectively. However, the effect of treatment type on growth of branches was not statistically significant, and the result would therefore not influence the protocol (Table 7). Between the two irrigation types, the results were perfectly consistent with drip irrigation showing better results over normal irrigation for all parameters (Table 8). The average increase in growth was 71% across the six parameters with leaves (204%) and branches (91%) recording the highest increase. The results showed high variability with a coefficient of variation value of 0.99. Descriptive statistics for the six growth parameters are presented in Tables 9 and 10.

5. Discussion

The analysis of post-mining terrain restoration is expensive and time-consuming, because of the number of complex connections between the various factors (Bieleckaa and Krol-Korczakb, 2010). Rehabilitation of abandoned red mud ponds is essential since it not only stabilizes the surface against wind and water erosion, but also provides an aesthetically pleasing landscape. Presently, there are no economically viable and environmentally acceptable solutions for effective utilization of the high residue volumes of red mud that are produced by aluminum companies. Tree planting is recognized for its ability to restore the soil fertility, build the ecosystem and arrest soil erosion. The ecological basis for the use of plantations for reclamation of damaged tropical lands has been described by many authors (Lugo et al., 1993; Lugo and Daniels, 1994; Parrotta, 1992; Rao and Tarafdar, 1998; Rao and Tak, 2002; Sharma et al., 2004b; Pandey, 2002; Pandey et al., 2005). Similarly, gypsum amendment to reduce the pH value of red mud was also described by many authors (Gherardi and Rengel, 2003; Williamson et al., 1982; Hinz, 1982).

The organic matters applied in this trial improve physical conditions, nutrient supply and provide a substrate for a burgeoning soil microbial community. Also, they protect the surface and reduce evaporation losses of water (Haynes, 2009). Similarly, vermicompost is a principal ingredient for the growth of plants. The worm

Table 7
Marginal means for treatment.

Treatment combination	Collar dia.	GBH	Height	Crown dia.	Leaves	Branches
C_0	0.216	0.118	9.362	8.020	47.707	1.054
C_1	0.245	0.125	10.380	8.909	59.717	1.176*
C_2	0.228	0.135	10.519*	8.804	52.136	1.079
C_3	0.250*	0.146*	10.343	9.438*	62.345*	1.162

* The highest value.

Table 8
Marginal means for irrigation type.

Irrigation type	Collar dia.	GBH	Height	Crown dia.	Leaves	Branches
Drip irrigation	0.265*	0.143*	11.721*	10.321*	83.500*	1.468*
Normal irrigation	0.204	0.119	8.580	7.264	27.452	0.768

* The highest value.

Table 9
Descriptive statistics for marginal means for species.

Species	Collar dia. (cm)	GBH (cm)	Height (cm)	Crown dia. (cm)	Leaves (no.)	Branches (no.)
Mean	0.208	0.090	8.104	7.704	31.510	0.554
Std. deviation	0.049	0.045	3.031	3.217	12.223	0.465
Co efficient of variation	0.234	0.502	0.374	0.418	0.388	0.839
Range	0.101	0.102	6.399	7.012	26.337	1.058
Range/mean	0.486	1.140	0.790	0.910	0.836	1.910

Table 10
Descriptive statistics for marginal means for treatment type.

	Collar dia. (cm)	GBH (cm)	Height (cm)	Crown dia. (cm)	Leaves (no.)	Branches (no.)
Average	0.230	8.578	10.028	1.098	0.126	53.187
Std. deviation	0.015	0.486	0.577	0.057	0.009	6.074
Coefficient of variation	0.063	0.057	0.058	0.051	0.068	0.114
Range	0.029	0.889	1.018	0.108	0.017	12.010
Range/mean	0.126	0.104	0.102	0.098	0.135	0.226

Table 11
Best fit results.

	Collar dia.	GBH	Height	Crown dia.	Leaves	Branches
Species	*Albizia lebbeck* and *Acacia nilotica*	*Acacia nilotica* and *Albizia lebbeck*	*Albizia lebbeck* and *Acacia nilotica*	*Acacia nilotica* and *Albizia lebbeck*	*Acacia nilotica* and *Albizia lebbeck*	*Albizia lebbeck* and *Terminalia arjuna*
Treatment combination	C3 and C1	C3 and C2	C2 and C1	C3 and C1	C3 and C1	C1 and C3
Irrigation	Drip	Drip	Drip	Drip	Drip	Drip

cast improves fertility, water retention capacity and porosity of the soil. A small amount of soluble organic matter penetrates the soil through macrospores, most of the added organic matter stay where it is deposited and serves as a food for microorganism. Bacterial strains are free-living nitrogen fixers, produce acid when grown at high pH and belong to *Azotobacter* and *Azospirillum* species. These bacteria enable the plant species to become more tolerant to stress by ensuring continuous supplies of nutrients during their early stages of growth. Acid-producing microorganisms are not available at all the places in alkaline/saline sites. Therefore, introduction of the selected efficient acid-producing microorganisms in alkaline soil/site is essential for the survival of plants at high alkaline site.

Gypsum is a calcium sulphate ($CaSO_4{\cdot}2H_2O$) that is used as source of Ca and S for vegetation and as soil conditioners to improve certain physiochemical properties of problematic soils. It improves the structure of the substrate through the exchange of Na for Ca and improves the pH reduction (USDA, 1954).

The results indicated positive changes in both physical and chemical properties of the red mud after completion of the project, which in turn impacted the growth parameters. The level of soil alkalinity reduced and so did the electrical conductivity. The impacts on growth parameters revealed clear patterns. Drip irrigation consistently gave a better result. Among five tree species *A. lebbeck* and *A. nilotica* scored over the other species. Both the species are drought resistant and can perform better in difficult sites. Among various treatment combinations, treatment C3 performed much better than the rest, which shows the positive impact at progressively higher levels of gypsum (Table 11). These results corroborate previous results of Sharma et al. (2004a) and Chauhan et al. (2006) where *A. lebbeck* and *A. nilotica* tree species exhibited a better growth rate on red mud by using gypsum, organic manure and acid producing bacteria at TERI's forestry research centre in Gual Pahari, Haryana and HINDALCO's red mud pond in Belgaum, Karnataka respectively (Plates 1 and 2).

Attempts like the one presented in this article has significance from the point of view of finding environmentally viable and ecologically acceptable solutions for effective utilization of large volumes of red mud generated by aluminum producing industries.

Plate 1. Research site pre-treatment.

This research trial standardizes the overall rehabilitation technique of red mud ponds by selecting suitable tree and grass species after experimenting with various treatment combinations, irrigation types and pit sizes. For successful establishment and growth of plantation, one also needs to focus on appropriate proportion of soil amenders, and other management practices suited to local edaphic and climatic conditions.

Efforts being made by HINDLCO to undertake plantation activities on red mud ponds in Belgaum, Karnataka and Muri, Jharkhand are the positive indications of uptake of the study results.

Plate 2. Research site post-treatment.

The strategies of rehabilitation outlined in this article should be helpful to mine managers in developing rehabilitation plans, and achieving a high standard of rehabilitation on red mud ponds for a sustainable closure (Ghose, 2005). India's demand for aluminum is on the increase since the beginning of this decade after a period of relative stagnancy. Enhancement of production capacities to meet this demand would necessitate robust plans for rehabilitation of red mud ponds. A carefully designed protocol would not just be cost effective and environmentally beneficial but would also enhance the corporate image of the producing companies.

Acknowledgments

The authors are grateful to HINDALCO, Chotamuri, Jharkhand, India, for financial and logistical support. Authors are thankful to Dr. C.S. Silori for his valuable comments.

References

Ash, H.J., Gemmell, R.P., Bradshaw, A.D., 1994. The introduction of native plant species on industrial waste heaps: a test of immigration and other factors affecting primary succession. J. Appl. Ecol. 31, 74–84.
Bagattto, G., Shorthouse, J., 1999. Biotic and abiotic characteristics of ecosystems on acid metalliferous mine tailings near Sudbury, Ontario. Can. J. Bot. 74, 410–425.
Barrow, N.J., 1982. Possibility of using caustic residues from bauxite for improving the chemical and physical properties of sandy soil. Aust. J. Agric. Res. 33, 275–285.
Bieleckaa, M., Krol-Korczakb, J., 2010. Hybrid expert system aiding design of post-mining regions restoration. Ecol. Eng. 36, 1232–1241.
Chauhan, S., Sharma, J.V., Lal, B., Paul, V., 2006. Rehabilitation of red mud pond: a pilot study at INDAL, Belgaum, Karnataka. Ind. For. 132, 534–542.
Chauhan, S., Silori, C.S., 2010. Rehabilitation of Red mud bauxite wasteland in India (Belgaum, Karnataka). Ecol. Rest. 28, 12–14.
Courtney, R., Mullen, G., Harrington, T., 2009. An evaluation of revegetation success on bauxite residue. Rest. Ecol. 17, 350–358.
Courtney, R., O'Neill, N., Harrington, T., Breen, J., 2010. Macro-arthropod succession in grassland growing on bauxite residue. Ecol. Eng. 36, 1666–1671.
Gherardi, M.J., Rengel, Z., 2003. Bauxite residue sand has the capacity to rapidly decrease availability of added manganese. Plant Soil 234, 143–151.
Gherardi, M.J., Rengel, Z., 2001. Deep placement of manganese fertilizer improves sustainability of Lucerne growing on bauxite residue: a glasshouse study. Plant Soil 257, 85–95.
Ghose, M.K., 2005. Soil Conservation for Rehabilitation and Revegetation of Mine Degraded Land. TIDEE (TERI Information Digest on Energy and Environment), 137–150pp.
Haynes, R.J., 2009. Reclamation and revegetation of fly ash disposal sites—challenges and research needs. J. Environ. Manage. 90, 43–53.
Hinz, D.A., 1982. Plants survive hostile bauxite residue. In: Australian Mining Industry Council Environmental Workshop, Darwin , Australian Mining Industry Council, Canberra, Australia.
Krishna, P., Reddy, M.S., Patnaik, S.K., 2005. *Aspergillus Tubingensis* reduces the pH of the bauxite residue (Red mud) amended soils. Wat. Air Soil Pollut. 167, 201–209.
Lee, J.A., Greenwood, B., 1976. The colonization by plants of calcareous wastes from the salt and alkali industry in Cheshire, England. Biol. Cons. 10, 131–150.
Lugo, A.E., Parrotta, J., Brown, S., 1993. Loss in species caused by tropical deforestation and their recovery through management. Amb 22, 106–109.
Lugo, R.S., Daniels, W.L., 1994. Nitrogen accumulation and form over time in young mine spoils. J. Environ. Qual. 23, 166–172.
O'Neill, C., Gray, N.F., Williams, M., 1998. Evaluation of the rehabilitation procedure of a pyritic mine tailings pond in Avoca, Southeast Ireland. Lan. Degrad. Dev. 9, 67–79.
Pandey, D.N., 2002. Sustainability science for mine spoil restoration. Curr. Sci. 83, 792–793.
Pandey, D.N., Chaubey, A.C., Gupta, A.K., Vardhan, H., 2005. Mine Spoil Restoration: A Strategy Combining Rainwater Harvesting and Adaptation to Random Recurrence of Droughts in Rajasthan. International Network on Ethno Forestry, Jaipur, India.
Parrotta, J.A., 1992. The role of plantation forests in rehabilitating degraded tropical ecosystems. Agric. Ecos. Environ. 41, 115–133.
Rao, A.V., Tak, R., 2002. Growth of different tree species and their nutrient uptake in limestone mine spoil as influenced by arbuscular mycorrhizal (AM)—fungi in Indian arid zone. J. Agric. Environ. 51, 113–119.
Rao, A.V., Tarafdar, J.C., 1998. Selection of plant species for rehabilitation of gypsum mine spoil in arid zone. J. Agric. Environ. 39, 559–567.
Schaaf, W., 2001. What can element budgets of false-time series tell us about ecosystem development on post-lignite mining sites. Ecol. Eng. 17, 241–252.
Sharma, J.V., Lhouvum, G., Chauhan, S., Paul, V., 2004a. Rehabilitation of red mud ponds at Belgaum. Ind. For. 130, 323–339.
Sharma, K.D., Kumar, P., Gough, L.P., Sanfilipo, J.R., 2004b. Rehabilitation of a lignite mine disturbed area in the Indian desert. Lan. Degrad. Dev. 15, 163–176.
Shu, W.S., Ye, Z.E., Zhang, Z.Q., Lan, C.Y., Wong, M.H., 2005. Natural colonization of plants on five lead/zinc mine tailings in Southern China. Rest. Ecol. 13, 49–60.
Skousen, J.G., Johnson, C.D., Garbutt, K., 1994. Natural revegetation of 15 abandoned mine land sites in West Virginia. J. Environ. Qual. 23, 1224–1230.
USDA, 1954. Diagnosis and Improvement of Saline and Alkali Soils. United States Salinity Laboratory Staff, Agricultural Hand book No. 60. United States Department of Agriculture, Washington DC.
Wild, S.A., Coret, R.B., Iyer, J.G., Voigt, G.K., 1979. Soil and Plant Analysis for Tree Culture. Oxford and IBH Publishing Co., New Delhi, India, pp. 1–218.
Williamson, N.A., Johnson, M.S., Bradshaw, A.D., 1982. Mine Wastes Reclamation. Mining Journal Books, London, United Kingdom.
Wong, J.W.C., Ho, G.E., 1991. Effect of gypsum and sewage sludge amendment on physical properties of fine bauxite refining residue. Soil Sci. 152, 326–332.
Wong, J.W.C., Ho, G.E., 1994. Sewage sludge as an organic ameliorant for vegetation of fine bauxite refining residue. Resour. Conserv. Recy. 11, 297–309.