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Full Length Research Paper

An evaluation of successful reclamation of bauxite residue through afforestation activities in south India

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The present article is based on the results of a pilot project implemented to improve the physico chemical characteristics of bauxite residue (red mud) in order to make it suitable for rehabilitation through afforestation activities. Prior to interventions, extensive experimentation on various reclamation trials involving combinations of soil amenders along with bacteria and mycorrhizae and selection of suitable tree and grass species was undertaken at the nursery stage for one year. During this period, five tree species and four grass/legume species were selected for afforestation program. Of the selected five tree species, *Prosopis juliflora, Acacia nilotica* and *Pongamia pinnata* responded well in combination with 55% red mud + 25% FYM + 15% gypsum + 5% vegetative dry dust + bacteria + mycorrihzae, while other two species, *Melia azedarach* and *Acacia tortilis* did not survive and thus were replaced by *Albizia lebbek* and *Leucaena leucocephala* during pilot implementation in 1.08 ha research plot of red mud of Hindustan Aluminium Company Limited (HINDALCO) at Belgaum, Karnataka, South India. Among the grass and legume species, all the selected four species namely: *Brachiaria mutica, Brachiaria decumbens, Stylosanthes scabra* and *Sesbania sesban* responded well at the nursery stage and thus were experimented at the research plot along with the tree plantation. Continuous monitoring on growth pattern of tree and grass species, and soil characteristics revealed remarkable changes in the physico chemical properties of red mud. Apart, toxicity of the planted species and other naturally grown herbaceous flora on the research plot of red mud was also tested for their edibility properties and the results were found encouraging.

Key words: Red mud, bacteria, mycorrhizae, tree species.

INTRODUCTION

Red mud is an insoluble waste material, generated during processing of bauxite to produce high grade aluminum, using the Bayer chemical process. The most common method for its disposal is storage in impounded dike deposits adjacent to the alumina processing plants (Krishna et al., 2005). The high alkali content of red mud deposits poses many environmental and health risks. Due to its hazardous nature, restoring ecological values of the deposit sites is a major challenge. There have been very few attempts in the past to rehabilitate the red mud residue deposits and bauxite mines wastes by establishing vegetation cover (Wong and Ho, 1994). However, extremely high pH and salinity accompanied by poor structure, water holding capacity and low microbial activity of the residue poses serious challenges. In a few and rear successful cases, it was reported that the nutrient concentrations in the red mud grown vegetation tend to be low, but can be increased to some extent by addition of ameliorants such as gypsum and sewage sludge (Wong and Ho, 1991). Gypsum can reduce the pH of the red mud through precipitation of hydroxides and carbonates by Ca^{2+} (Barrow, 1982). Gypsum is a calcium sulphate ($CaSO_4$ $2H_2O$) and reduces alkalinity through $CaCo_3$ formation. It also improves the structure of the substrate through the exchange of Na for Ca, which help in reducing pH as the Ca absorbs OH. Red mud closely resembles with alkali soil in respect of high pH and ESP and the associated physico chemical properties and,

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Table 1. Terrace wise plantation of the tree species during pilot phase.

S/No.	Terrace No.	Size of terrace	No. of plantation rows	Total number of individuals planted
1	Terrace – I (2400 sq. mt.)	80 m × 30 m	14	154
2	Terrace – II (2800 sq. mt.)	80 m × 35 m	16	198
3	Terrace – III (3200 sq. mt.)	80 m × 40 m	21	283
4	Terrace – IV (2400 sq. mt.)	80 m × 30 m	20	160
Total	10800 sq. mt.		71	795

hence is likely to react in a similar way to gypsum. The present research was conducted at the red mud deposit pond of aluminum refineries of Hindustan Aluminum Company Ltd. (HINDALCO) at Belgaum, situated at northwest part of Karnataka State in South India. This refinery commenced operation in 1969 with an initial capacity of 75,000 metric tons of alumina hydrate per annum. Subsequently, the plant was expanded twice, first time in 1993 to a level of 220,000 metric tons per annum and later in 1996 to 260,000 metric tons per annum. This refinery generates a voluminous quantity of 400,000 metric tons per annum of waste in the form of red mud.

HINDALCO has earmarked 69 hectares of land for the red mud disposal close to the refinery in the form of two specially constructed ponds measuring 30 and 39 hectares respectively. Pond 1 has been in use since 1985 and about 80 to 85% of it is filled with red mud, while Pond 2 is proposed to be used after Pond 1 is completely filled up. Thus, the findings presented in this article are based on the experiments conducted at 1.08 hectare area of one of the sites in Pond 1 for its ecological reclamation.

METHODOLOGY

The reclamation of red mud pond was essentially based on experimentation of the vegetative treatment at nursery stage and scaling it up at the red mud pond site on pilot basis. The entire approach thus, included two major phases, spanning over 5 years from 2002 to 2007. The first phase consisted of nursery experiments with selected plant species grown under different set of treatments and the second phase was to execute the nursery level results to the pilot stage implementation. In this paper we are describing the findings of the pilot phase plantation activities, while the results of the experiment phase have been published earlier (Sharma et al., 2004; Chauhan et al., 2006).

Reclamation design

Experiment on reclamation of red mud through afforestation activities was carried out from January to December 2002 at TERI's nursery at Gual Pahari in Haryana state. For the research experiment, 3 tons of red mud was transported from HINDALCO, Belgaum, Karnataka to the nursery site. At nursery stage, three combinations of soil amenders along with red mud were developed. Each combination was further inoculated with bacteria and mycorrhizae in isolation and in combination. Thus, each combination had a total of 4 treatment sets: (i) without inoculation of bacteria and mycorrhizae; (ii) with bacteria; (iii) with mycorrhizae and (iv) with bacteria and mycorrhizae, forming a set of total 12 treatments, while the 13th treatment was a controlled one, without any amenders, just the red mud. Results of the nursery experiment revealed that out of total 13 different treatments sets, a combination of 55% red mud + 25% FYM (farm yard manure) + 15% gypsum + 5% vegetative dry dust + bacteria + mycorrhizae was found most suitable for the growth and survival of tree and grass species. Among the selected five tree species, *Prosopis juliflora* (Vilayati Babul), *Acacia nilotica* (Kikar), and *Pongamia pinnata* (Karanj), responded satisfactorily, while *Melia azedarach* (Drek) and *Acacia tortilis* (Israeli Babul) did not survive. All the selected four grass and legume species namely: *Brachiaria mutica* (Para grass), *Brachiaria decumbens* (Signal grass), *Stylosanthes scabra* (Shrubby stylo grass) and *Sesbania sesban* (Sesban) performed well. The aim of identifying the best suitable tree and grass species and amenders at the nursery stage was to improve the physico chemical characteristics of red mud through afforestation activities. The selection of tree and grass species was driven by some of their favourable properties towards the restoration process such as, high tolerance towards alkaline and saline soils, relatively fast growth rate, soil binding properties and also to supply the biomass to local people in the form of fuelwood and fodder (Sharma et al., 2004). Immediately after the success of nursery experiments on red mud, we took an area of 1.08 ha from one of the two red mud ponds of the HINDALCO for pilot implementation of the nursery findings during the month of January 2003. Before plantation activities, we worked out on the details of procuring seeds, FYM, gypsum, vegetative dust, raising seedlings, drawing up plans for earth work such as leveling and pit digging and arranging other logistics such as water supply to the pilot research plot etc. For raising saplings, seeds of the selected tree species were collected from the seedling seed orchards of Forestry Research Center of TERI and germinated them in HINDALCO's nursery in the later half of March 2003. At this stage, we replaced *M. azedarach* (Drek) and *Acacia tortilis* (Isreali Babul), which did not perform well during the nursery experiment, with *Albizzia lebbek* (Kala Siris) and *Leucaena leucocephala* (Leucaena) respectively.

The earthwork such as leveling and pit digging was started in the middle of April 2003 with the help of JBC machine. Due to undulating slopes and hilly terrain at the redmud pond, the research plot was divided into four terraces along the slopes. Total 795 pits were dug, keeping a distance of 4 × 3 m between rows and pits. Each pit had a size of 45 × 45 × 45 cm. Immediately after completion of pit digging, plantation was started in the month of May 2003. The selected tree species were planted alternately on all the four terraces. *P. juliflora* was followed by *A. nilotica, P. pinnata, A. lebbek* and *L. leucocephala* respectively (Table 1). At the time of plantation the saplings were little over 2 months old and had attained a height of 30 to 45 cm. Each pit was filled with 5 kg of gypsum, 7 kg of FYM and 1.5 kg of dry vegetative dust. Thus, for entire research plot, we used approximately 4 tons of gypsum, 6 tons of FYM and little over 1 ton of vegetative dry dust. Seeds of grass and legume species were procured from Indian Grassland

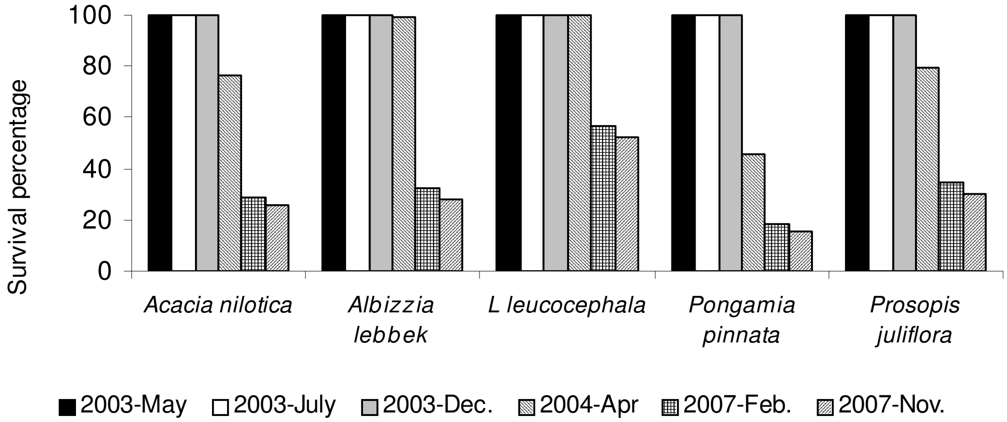

Figure 1. Survival percentage of tree species.

and Fodder Research Institute (IGFRI), Jhansi, except for *Brachiaria mutica* for which seeds were not available and therefore, we procured root slips from local Forest Department's nursery for plantation. In between the two rows of tree plantation, one row of grass/legume species was planted, keeping a distance of 30 cm between two seeds or root slips. In order to ensure good survival and growth of the planted trees and grass and legume species, we installed drip irrigation system for continuous and uninterrupted water supply at the research plot site. Two overhead water tanks with a cumulative capacity of 8000 liters were placed and connected through drip irrigation system. Approximately, each sapling was watered 8 to 10 L everyday through out the year, except the monsoon season. Monitoring of the restoration activities was started immediately after tree plantation was completed by the end of May 2003 and continued until April 2004 at an interval of every 2 to 3 months. In order to further investigate the establishment of the restoration process, another round of monitoring was done in 2007, during February and November.

Plantation monitoring

Monitoring was done regularly for assessing the survival and growth of plantation and changes occurred in physico chemical properties of red mud. We started monitoring in May 2003 and continued till April 2004 at an interval of every 2 to 3 months. Again after a gap of almost three years, monitoring was further carried out in February 2007 and November 2007. Thus, we had a total of 6 monitoring, based on which the growth patterns of the planted tree and grass species and characteristics of red mud are described. The parameters monitored to assess the growth of tree species included girth of the stem, height and survival percentage. For the grass species, primarily density that is (no. of individual tufts/sq. m) and shoot length were reported.

Toxicity detection of the vegetation

During the last monitoring phase in November 2007, we also reported extensive growth of the other naturally grown herbaceous flora, including climber (*Momordica* spp.), grass (*Clitoria* spp.) and few vegetables crops such as *Lycopersicon esculentum* (tomatoes), *Phaseolus* spp. (beans) and grains such as *Eleusine coracana* (finger millet). It is believed that these species must have grown in the area due to the seed dispersal by birds and may be by few grazing animals. However, since these species were growing in the hazardous red mud, we were not sure about their edible properties. Therefore, the samples of the vegetables and grain crops and even fodder grass were collected and laboratory tests were conducted. The collected samples were analyzed for detecting pesticide residue, using GC mass full scan analysis, heavy metal residue and natural toxin residue. In the heavy metal residue analysis, we tested for the presence of "cadmium, lead, mercury, nickel and chromium" while in natural toxin residue analysis we tested for aflatoxin (B1, B2, G1 and G2).

Red mud properties

In order to know the changes occurred in the characteristics of red mud due to vegetation growth, we collected samples of red mud from the different depths namely, 15, 30 and 45 cm during each monitoring. From each depth, we collected five samples and mixed them to analyze for number of parameters to detect the changes occurred in the physico-chemical properties of red mud after the treatment.

RESULTS

Performance of tree species

Survival of tree species

The results of the overall survival percentage of tree species are presented in the Figure 1. In the first year of the plantation, survival percentage was reported quite encouraging in all the terraces, averaging around 80%. This can be considered quite high, particularly in view of the unfavorable soil characteristics of the pilot site. It is however, important to report that the survival percentage declined sharply to 30% during latest monitoring done in early and late 2007. We reported couple of basic reasons for this. Firstly, the extensive growth of the grass, which attained an average height of more than 2 meter during every growing season, severely limited the space for other species to grow. Secondly, the profuse growth of grass resulted in the abundant production of grass seeds,

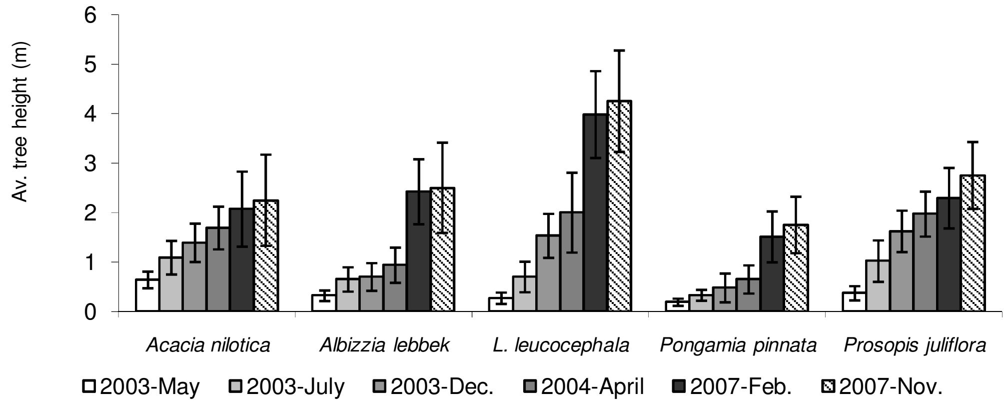

Figure 2. Patterns of average tree height for the planted species.

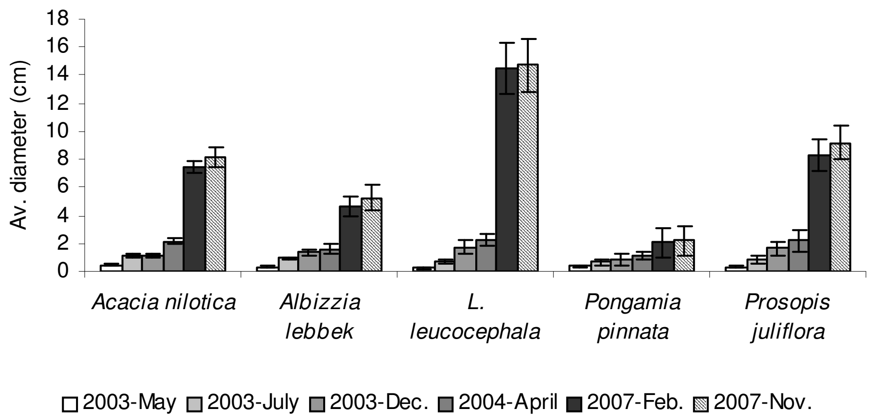

Figure 3. Patterns of average growth in the stem diameter.

and thus providing ideal habitat for the rodents and other burrowing animals to feed and make their burrows under thick vegetation. Finding ideal habitat, these animals started destroying the root zones of adjoining trees, leading to their mortality, and thus drastically reducing their numbers in the plot.

Tree height

Among the selected five species, *L. leucocephala* attained the maximum average height. From an average height of 0.27 m in 2003 to 4.25 m, reporting nearly 16 times increase in November 2007. This was followed by *P. pinnata* (9 time increase from 0.19 m to 1.75 m). *A. nilotica* reported the least growth, reporting about 3.5 times increase in height in 4.5 years duration (Figure 2).

Stem girth

Similar to the height, *L. leucocephala* also reported maximum growth of the stem diameter. As presented in Figure 3, average growth of stem diameter in case of *L. leucocephala* increased from 0.27 to 14.75 cm, reporting almost 57 times increase. This was followed by *P. juliflora* reporting about 27 times increase, while *A. nilotica* and *A. lebbek* reported almost similar growth rate around 17 times and *P. pinnata* reported the least around 5 times increase in 4.5 years duration.

Performance of grass and leguminous species

Monitoring of the growth of the grass and leguminous species was done 4 times during the whole study period namely: December 2003, April 2004, February 2007 and November 2007. Monitoring of the density of grass tufts and average height indicated that *B. mutica* and *B. decumbens* dominate other two grass species and showed high tolerance to the adverse soil conditions and therefore reported continuous growth during monitoring period. On the other hand *S. scabra* did not perform well and therefore was not reported in the latest monitoring

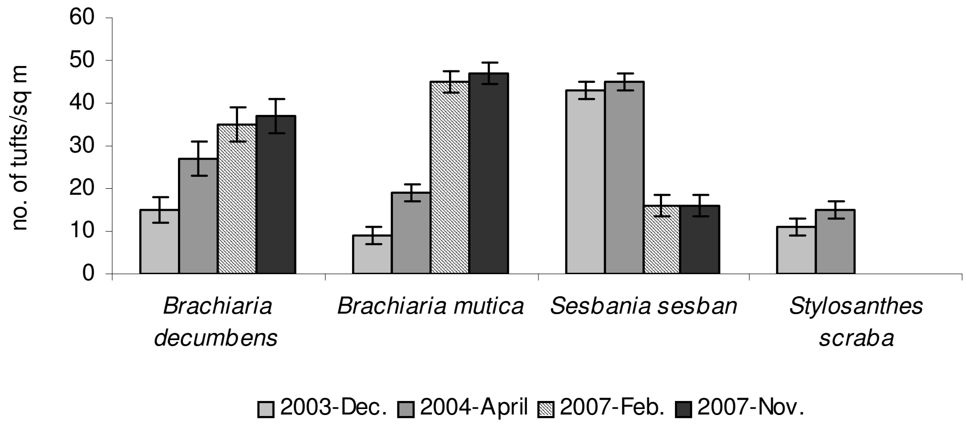

Figure 4. Patterns of average density of grass and leguminous species.

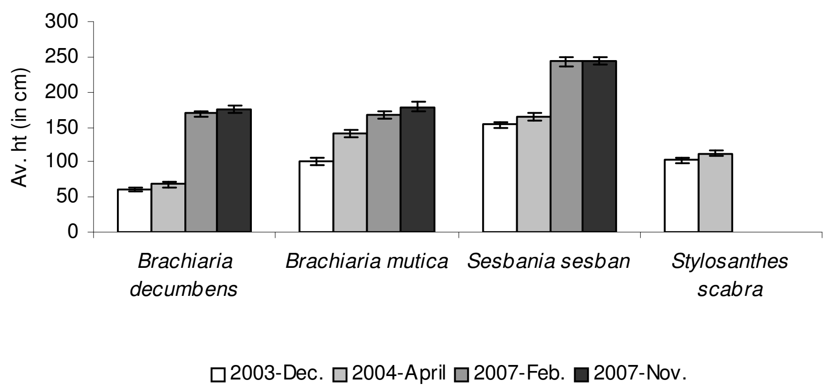

Figure 5. Patterns of growth in the average height of grass and leguminous species.

during 2007. The leguminous species, *S. sesban* reported moderate growth with declining trend in the latest monitoring (Figures 4 and 5).

Soil characteristics

The results of soil analysis from various depths indicated positive changes in both physical and chemical properties of the red mud. Sand contents reported an increase, while silt and clay contents decreased at all the three depths. While on one hand, pH values reported a decline, micronutrients and total bacterial population reported noticeable increase, which ultimately made the edaphic environment suitable to grow the vegetation and sustain it. The soil texture class, however, remained sandy loams (Table 2).

Toxicity of the vegetation

The toxicity results of the grass and few other vegetable crops were found negative as all the samples were reported edible. The test results for all the parameters were well within the permissible limit of prevention of food adulteration (PFA). According to the laboratory test results, the grasses could be used for fodder while vegetables and crops are edible. This indicates the improving quality of soil, which is able to provide habitat to the diversity of flora and fauna (Tables 3 and 4).

DISCUSSION AND CONCLUSION

Mining operations and associated activities degrade significant area of land, causing environmental and ecological damage to the existing ecosystems and landscapes with the dumping of undesirable waste materials in the form of mine spoil and also in the form of untreated excavated voids. 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

Table 2. Changing patterns in physical and chemical properties of the red mud.

Soil parameters	15 cm depth		30 cm depth		45 cm depth	
	May 03	Nov.07	May 03	Nov.07	May 03	Nov. 07
pH value	8.20	7.00	8.30	7.73	8.40	8.00
EC (ds/m)	8.30	2.20	8.68	2.83	10.00	2.75
Exchangeable sodium (Me/100 g)	85.00	94.00	83.00	84.20	80.00	80.50
Organic carbon (%)	0.92	0.98	0.65	0.66	0.61	0.60
Available nitrogen (kg N/ha)	229.00	230.96	160.00	165.10	152.00	158.12
Available phosphorous (kg P/ha)	90.30	95.88	72.10	74.97	61.20	68.26
Available potassium (kg K/ha)	3800.00	6352.18	2912.00	9458.84	2688.00	11293.44
Total bacterial population (cfu/gm soil)	3×10^5	1.8×10^9	$2x10^4$	1.0×1^8	Nil	1.6×10^2
Soil texture						
Sand (%)	66.10	68.60	64.10	56.72	66.10	60.40
Silt (%)	15.70	15.26	18.80	24.63	16.00	24.50
Clay (%)	18.20	16.14	17.90	18.65	17.90	15.10
Texture class	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam

Table 3. Toxicity levels of grass species.

Test/parameters	Response			Prevention of adultera	Detection limit
	B. mutica	*S. scabra*	*B. decumbens*		
Pesticide residue - GC mass full scan analysis (mg/kg)					
Y – BHC	0.048	0.084	0.013	1.0	
β – BHC	0.052	X	X	1.0	
Aldrin	X	X	0.0056	0.1	
Heavy metal residue analysis (mg/kg)					
Cadmium	X	X	X		0.1
Lead	X	X	X		0.5
Mercury	X	X	X		0.01
Nickel	X	X	X		0.5
Chromium	0.505	X	0.954		0.5
Natural toxin residue analysis (µg/kg)					
Total aflatoxin (B_1, B_2, G_1, G_2)	X	X	X		1.0

X: Not detected.

et al., 1993; Lugo and Daniels, 1994; Rao and Tarafdar, 1998; Rao and Tak, 2002; Sharma et al., 2004; Pandey, 2002; Ghose, 2005; Pandey et al., 2005). As compared to many other mining sectors, reclamation of red mud is a real challenge in view of the extreme high pH and almost non existence of any nutrients to support the growth of any kind of vegetation. 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 the aluminum companies. The main environmental risks associated with bauxite residue are related to high pH and alkalinity and minor and trace amounts of heavy metals and radionuclides. In view of this, attempts like the one presented in this article has significance from the point of view of finding environmentally and ecologically acceptable solutions for effective utilization of large volumes of red mud generated by aluminum producing industries. This research could stabilize and standardize the reclamation of red mud ponds by selecting suitable tree and grass species. Rigorous selection of the species after experimenting with various treatment combinations, preparation of ideal combination of soil amenders such as FYM, vegetative dust, gypsum, bacteria and mycorrhizae to provide suitable growth medium were key factors to establish and sustain the vegetation growth on

Table 4. Toxicity level of vegetables and crops.

Tests/parameters	Results				Prevention of Adulteration limit	Detection limit
	Lycopersicum esculantum	***Phaseolus* spp.**	***Momordica* spp.**	***Eleusine coracana***		
Pesticide Residue - GC mass full scan analysis (mg/kg)						
Y – BHC	X	X	X	X	1.0	
β – BHC	X	X	X	X	1.0	
Aldrin	X	0.0096	0.0067	0.0046	0.1	
Heavy metal residue analysis (mg/kg)						
Cadmium	X	X	0.57	X		0.1
Lead	X	X	X	X		0.5
Mercury	X	X	X	X		0.01
Nickel	X	X	X	X		0.5
Chromium	X	X	X	X		0.5
Natural toxin residue analysis (µg/kg)						
Total aflatoxin (B_1, B_2, G_1, G_2)	X	X	X	X		1.0

X: Not detected.

the red mud affected land substratum in the pilot site. Results of the growth patterns of the planted vegetation are indications of such successful initiative. Though the survival percentage of trees substantially declined in the recent monitoring, the reason for that was mainly linked to the damage of the root zone caused by the rodents.

Parrotta et al. (1997) revegetated the bauxite mine degraded areas in Brazil, using the topsoil planted with the native species (Parrotta et al., 1997; Parrotta and Knowles, 1999). The authors concluded that mixed native species reforestation approach was very successful for the bauxite mined area in the Brazilian Amazon region. Another important feature of this intervention was significant changes in the quality of red mud in the form of decline in the pH, providing ideal habitat for the planted species to establish and grow. The research work confirmed reduction in pH value, improved proportion of sand, and increased micronutrients. All these changes provided much needed nutritional support to the growing plants. Besides, planted species, emergence of other herbaceous flora, not reporting any toxic characteristics, can be considered important indicators of improving health of the red mud substratum. Growth of few vegetables and crops in the plot also indicate improving faunal diversity, especially bird species, which act as seed disperser and thus enrich the ecosystem health. Besides birds, few reptiles (garden lizard), small mammals (rabbit, squirrels) and other burrowing animals (shrews) were also reported from the pilot plot. All these developments confirmed the environmental and ecological compatibility of the rehabilitated red mud significantly improve the probability of long term success of restoration efforts (Parrotta, 1992). In order to ensure the sustainability of the pilot implementation, we also conducted training and capacity building of the field staff of HINDALCO, who replicated the pilot model and expanded the reclamation plan to another 4 ha area of red mud pond. Results of the replication efforts by HINDALCO during past three years have been very encouraging and this has helped in sustaining the initiative taken under this project. Thus, it can be summarized that the present research work has been able to standardize the techniques of reclamation of the highly alkaline red mud affected land surface with very high possibilities of replication and long term success of restoration efforts. For successful establishment and growth of plantation, we focus largely on correct choice of species, soil working methods, planting techniques, appropriate proportion of soil amenders and other management practices suited to local edaphic and climatic conditions. However, we believe that there is still huge scope for further in depth research in this area through focusing on maximum utilization of rainwater, more efficient and cost effective soil working and planting techniques, spot treatment only at the planting site, soil treatment up to a deeper zone and not confined to 10 to 15 cm, keeping minimum salt concentration in the active zone of young plants through leaching etc.The findings of this program will be certainly useful for the aluminum producing industries, which are facing serious challenges to find an economically viable and environmentally acceptable solution for treating large volumes of red mud deposits. Scaling up of the pilot scale results at the present site and replication of the research findings in another site by HINDALCO in eastern India are indications of this.

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