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Identification of indicator species at abandoned red mud dumps in comparison to residential and forest sites, accredited to soil properties

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ABSTRACT

Plant community structure studies on derelict sites are providing significant insights into vegetation dynamics to ensure the success of future revegetation projects in such areas. Therefore, the present study was conducted to evaluate the changes in soil physico-chemical and biological properties at abandoned red mud dumps (RMD) compared to residential (RS) and forest (FS) sites, coupled with their consequent impacts on the plant community structure. An attempt was also made to identify the indicator species that thrive only under unfavourable red mud conditions. Soil at RMD showed relatively high bulk density, alkalinity, salinity and exchangeable sodium percentage along with poor nutrient status and low microbial activity. Though toxic metals (Cd, Cr and Pb) were higher at RMD, their phytoavailabilities were lower compared to FS site. Number of herb-, shrub- and woody species at RMD were although low, but a significant number of species were acclimatized to the unfavourable soil conditions. Shrub species were maximally affected at RMD, followed by woody- and herbaceous species. Important value index of sensitive species was low while that of tolerant species was higher, and was accredited to altered soil properties. Presence of invasive species such as *Acacia nilotica*, *Caesalpinia bonduc*, *Stylosanthes scabra* and *Urena lobata* at only RMD may be used as an indication for high toxic metal contamination along with high alkalinity, salinity and poor nutrient contents. Principal component and canonical correspondence analyses revealed that woody and herbaceous species were mainly affected by soil alkalinity, salinity, exchangeable cations, bulk density, porosity, moisture content and phytoavailable metals. Shrub species were primarily influenced by soil organic carbon, nitrogen, available phosphorus, bulk density, porosity, moisture content, soil biological parameters, total (Fe, Mg, Cd, Cr and Pb) and phytoavailable metals. Domination of herbaceous species in the plant community indicated their tendency towards a definite selection strategy in response to altered soil properties. The identified tolerant herbaceous species may be suitable candidates for future red mud reclamation strategies.

1. Introduction

Aluminium, the third most abundant element in the Earth's crust, is widely used in packaging, transportation, construction and industrial sectors. Alumina is extracted through Bayer's process where bauxite ore is treated with hot caustic soda under elevated temperature and pressure. Approximately, 85–90% of bauxite is converted to alumina followed by Hall–Héroult process for aluminium production (Liu et al., 2009). Depending upon the efficiency of the process and quality of the ore used, per tonne production of alumina generates 1.9–3.6 tonnes of bauxite residue, commonly referred to as “red mud” (Hind et al., 1999). Due to the high demand for aluminium, red mud generation has been reached to ~150 million tonnes per annum globally (Evans, 2016). Disposal of such a huge quantity of waste includes marine/slurry disposal, dry stacking and dry cake stacking. At present, dry cake stacking is highly adopted as it attempts to produce 65–70% solid cake before disposal which minimizes land acquisition and reduces the risk of environmental contamination (Xue et al., 2016b). Improper disposal of poorly treated residue may lead to several environmental problems with its consequent impacts on the living beings (Mayes et al., 2016). For instance, in the aftermath of Ajka red mud spill in Hungary resulted in respiratory problems from fugitive dusts, ground-water contamination due to leaching, and prolonged toxic effects of high soda and metal (oid) contents on soil properties, plant performance and possible food chain contamination (Mayes et al., 2016).

Red mud is characterized by high alkalinity, salinity, electrical conductivity and exchangeable sodium percentage. Furthermore, lack of structural stability promotes seal and crust formation thereby

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affecting water and air movement, root penetration, seedling emergence and tillage (Courtney et al., 2009b). Texture analysis of red mud showed 0–30% sand, 9–66% silt and 26–80% clay (Xue et al., 2016b). Due to low particle size (< 2–2000 μm), red mud has high bulk density, and low hydraulic conductivity, porosity and water holding capacity (Nguyen and Boger, 1998). Aging of red mud led to transformation of fine-textured red mud (silty loam) to coarse-textured material viz. residue sand (sandy loam) due to natural weathering process in the time span of 20 years (Zhu et al., 2016c). The XRF analysis of red mud revealed the major constituents as Al_2O_3 (6.4–30%), Fe_2O_3 (5–71.9%), SiO_2 (0.6–54%), TiO_2 (1–18%) and Na_2O (0.3–12.1%) (Xue et al., 2016b). Besides, it is characterized by high levels of potentially toxic metal(oid)s such as Al, Pb, Cr, As, Cd, Ni and V (Gautam and Agrawal, 2017; Mišík et al., 2014) and low levels of available nutrients viz. K, Zn, Mn, Co, Mg and Cu (Akinci and Artir, 2008).

There are several advanced red mud management techniques such as metallurgical processes, catalytic applications, manufacture of pigments, paints, adsorbents, ceramics and construction materials (Xue et al., 2016b; Wang et al., 2008). But all these options are neither eco-friendly nor cost-effective and require refinement before the residue can be used successfully. Indeed, only 2–3% of ~150 million tonnes of bauxite residue generated per annum is utilized in a productive manner (Evans, 2016). The long lasting and cost effective solution for this problem lies in the establishment of permanent vegetation cover on RMD (Xue et al., 2016b). Establishment of habitat for flora, fauna and microorganisms on abandoned wastelands are generally used as ecological indicators of soil structure and its nutrient status (Sheoran et al., 2010). Soil structure is a fundamental property which plays a significant role in nutrient transport, soil moisture content and gas exchange as well as establishment of habitat for living organisms (Schoonover and Crim, 2015). Therefore, prior to rehabilitation by revegetation, the physico-chemical properties of red mud liable to cause adverse effects on plants need to be counterbalanced either naturally or by using suitable amendments. Studies have been conducted on revegetation of RMD by utilizing various ameliorants viz. bio-wastes (sewage-sludge, compost, vegetative dry dust and animal manures), microbes (bacteria and fungi), gypsum, seawater neutralisation and carbonation, which improved soil properties and plant performance by increasing the stability of soil aggregates, organic matter and nutrient contents as well as alleviated alkalinity, salinity and phytotoxicity (Ujaczki et al., 2017; Santini et al., 2015; Courtney and Harrington, 2012). Organic amendments to sodic soils stimulate microbial decomposition of organic matter, leading to the production of soil-aggregate binding agents thereby promoting aggregation and formation of granular soil structure (Xue et al., 2016a). Fresh RMD are extremely non-supportive towards plant growth, but 5–10 year old RMD was found to support a few plant species due to a decrease in pH, ESP, EC and an increase in available nutrients (Liu et al., 2007).

Plant community carries out various biological services in an ecosystem viz. preventing soil erosion, reducing the risk of local and global climate change, recycling nutrients, pollination and biological control of diseases, controlling pollutants and providing economic values (Pandey et al., 2014). Plant species are distributed in variable habitats, but abundance of species in a particular area represents their ecological optimum, and hence the composition of plant communities is a function of changing habitat conditions along environmental gradients (Pellissier et al., 2013).

There are several reports available around Renukoot in Sonbhadra district of Uttar Pradesh related to forest structure and function as well as medicinal plants (Kumar et al., 2015; Singh and Dubey, 2012; Singh et al., 2012). However, no studies were conducted regarding the changes in plant community structure pattern at abandoned RMD or urban forests. Therefore, an attempt was made for the first time to evaluate the changes in soil properties and variations in plant community structure at abandoned RMD in comparison to residential and forest sites. Indeed, native forest and residential (urban) areas are likely to provide good comparators as dominant land use types and potentially useful analogues for undisturbed and human intervened ecosystems, respectively. Notably, native forest and residential areas are at their late successional stage (climax community), whereas abandoned RMD were under the stage of spontaneous revegetation. The study also includes the identification of potential plant indicators susceptible towards unfavourable conditions of RMD.

2. Materials and methods

2.1. Study sites

HINDALCO Industries Ltd., Renukoot (24.2° N; 83.03° E and 283 m above mean sea level), the second largest alumina refinery in India, is known to generate approximately 2.06 million tonnes of red mud annually (Samal et al., 2013). At present, generated residue is disposed off in the form of 70% solid cake at a dumping yard. The present study was carried out during 2014–2016 at 16-year-old abandoned RMD, ~250 m from the premise of HINDALCO Industries Ltd. (latitudes 24° 14′ 06.21″ N, longitude 83° 01′ 52.21″ E, 291 m above mean sea level) and a residential site (RS) (latitudes 24° 12′ 57.74″ N, longitudes 83° 01′ 59.86″ E, 294 m above mean sea level). Forest site (FS) acted as a reference site (latitudes 24° 13′ 16.80″ N, longitudes 83° 00′ 55.41″ E, 348 m above mean sea level) for both RS and RMD for comparing soil properties and plant community structure. All the three study sites are located in Renukoot, situated in the central part of Sonbhadra district, in the state of Uttar Pradesh, India. FS is situated approximately 4.25 km in south-west direction from RMD and 3.38 km in north-west direction from RS, respectively. Large areas of Renukoot were once covered with natural forest with small and interspersed tribal dwellings. The establishment of HINDALCO Industries Ltd. in 1958 led to land clearance for developmental activities which resulted in rapid immigration of human population, deforestation and conversion of natural forest ecosystems into marginal croplands and urban settlements. Pratap (1997) showed a LULC map of Obra-Renukoot region revealing forest area (343.5 km^2), agricultural land (143.4 km^2), plantation (17.24 km^2), water bodies (40.65 km^2), mining/industrial coverage (8.8 km^2), build-up areas (5.6 km^2) and wastelands (50.75 km^2). A decline in forest coverage by 12.82 and an increase in build-up area by 44.9% are primarily attributed to the developmental activities in the area (Chopra, 2011).

The study area experiences tropical monsoon climate with three seasons in a year, summer (April–mid June), rainy (mid June–September) and winter (November–February). Months of March and October represent seasonal transitions between winter and summer and rainy and winter, respectively. The variations in meteorological parameters in the area are given in Fig. 1.

2.2. Soil sampling and analyses

Each of the three sites was subdivided into ten subsites (Table S.1) for soil sample collection to assess their physico-chemical and biological properties (Fig. 2). Soil samples were collected using soil corer (5 cm diameter and 10 cm depth) from three places of each subsite, every 4 months for three consecutive years from 2014 to 2016. The soils from three replicate sites of subsites were mixed together to form a composite soil sample. Thereafter, soil samples were air dried, ground to pass through 2 mm sieve and three replicates were used for various analyses. For bulk density and porosity, soil was collected up to the depth of 10 cm using the soil corer (5 cm diameter), while for moisture content, 10 g soil sample was oven dried at 80 °C until a constant weight was attained. The pH and EC were measured through pH meter (Model EA940, Orion, U.S.A.) and conductivity meter (Model 303, Systronics, India), respectively. Available phosphorous (AP), total organic carbon (TOC) and total nitrogen (TN) were assessed using Olsen's method (Olsen et al., 1954), Walkley and Black's rapid titration method