ABSTRACT

Chromite ore processing residue (COPR) is a hazardous industrial waste derived from the chromate (CrO_4^{2-}) extraction roasting process. It is one of the major sources of environmental contamination as it contains high amounts of chromium (Cr) in, both, the hexavalent [Cr(VI)] and the trivalent [Cr(III)] valence states. COPR has been disposed of in unregulated surface (unlined) landfills in several nations across the world, including India, without consideration to its (eco)toxicological potential. It is among the most environmentally hazardous industrial chromium wastes, posing a threat to both human health and the environment. The leaching of Cr(VI), resulting in the contamination of groundwater, is a key environmental risk arising from these COPR dumps. Therefore, the remediation of COPR is of utmost importance, especially at contaminated sites where it was disposed of in an unscientific manner.

COPR from two of the legacy waste-contaminated sites [Ranipet (TCCL, Tamil Nadu, India) and Rania (near Khan Chandpur village, Kanpur Dehat, Uttar Pradesh, India)] are collected and characterized. Metal content analysis and TCLP-based leaching analysis were performed to arrive at detailed waste properties. In addition to the physicochemical characterization of COPR waste from both sites, the mineralogical composition was also evaluated. The complexity of chromium chemistry, the high exposure risk potential posed by COPR, coupled with the quantity of wastes at these sites advocate for an urgent need to remediate them, and demands the development of a remediation framework that can address the difficulties posed when handling multiple criteria.

National-level clean-up standards (or remediation targets or intervention values or guidelines) associated with Cr-contaminated sites are established only for a few countries. Upon detailed literature review, two sets of standards (Canadian and Dutch) were considered. Considering the two selected COPR sites and two remediation standards, four combinative cases were formulated.

The most appropriate technology alternative for COPR remediation in each of these four cases would be estimated using a multi-criteria framework.

Various aspects regarding the remediation of Cr-contaminated sites that have COPR as the major source of Cr are studied in existing academic literature and databases. A panel of experts (with 4 stakeholder groups) was queried in a 3-phase (4-stage) Delphi process about such aspects of COPR remediation that were not gathered in the literature survey. Their opinions are used to — ascertain and shortlist relevant criteria, create a 'pair-wise comparison matrix' among selected criteria, identify candidate treatment technologies for COPR remediation, and generate an 'information evaluation matrix' between remediation technology and criteria.

A novel resourceful multicriteria analysis framework, PROSPER-COPR [Prioritization of Remedial Options through Systematic Parametric Evaluation and Ranking for contaminated sites having Chromium Ore Processing Residue (COPR) overburden], was developed to arrive at the weights for finalized criteria and to determine the ranking between alternative technologies. Though POSPER can be applied to any remediation of any waste-contaminated site, PROSPER-COPR is directed towards addressing legacy COPR overburden at contaminated sites. As part of the PROSPER-COPR framework, a variety of multicriteria decision-making (MCDM) methods and weighting methods were employed to calculate criteria weights (both, weights applicable to any site and case-specific weights), as well as to evaluate the rankings between the considered remediation technology alternatives. Fuzzy-AHP, Entropy, and CRITIC methods were used for the calculation of weights; and, TOPSIS and PROMETHEE-II were applied to determine the ranks among various shortlisted remediation technologies. Upon arriving at the case-specific optimal solutions, a novel 'Technology Improvement Need Analysis (TINA)' framework has been developed to perform the efficiency analysis of all the remediation technology alternatives or

decision-making units (DMUs) for all cases. The aim of measuring the efficiency of DMUs is to quantify the magnitude by which each of the suboptimal alternatives must be improved for every criterion in order for them to become the optimal candidate of choice.

To measure the efficiency of DMUs, two non-parametric deterministic mathematical multi-objective decision-making (MODM) tools — the Data Envelopment Analysis (DEA) method and the Free Disposal Hull (FDH) method, are used. Two well-known basic DEA models i.e., Charnes, Cooper, and Rhodes (CCR) model and Banker, Chames, and Cooper (BCC) model, are considered, both, with input orientation. Appropriate solutions are proposed for physically improving the criteria-wise performance of the technologies before their field implementations. The research outcomes are expected to provide an all-inclusive framework to decision-makers across the world for effective remediation of COPR at existing sites, which can be easily replicable to any toxic and hazardous waste.

Keywords: Heavy metal contamination, Chromite Ore Processing Residue, COPR, Contaminated sites, Remediation, Delphi method, MCDA.