Doctoral School of Chemical Engineering and Material Sciences

University of Pannonia

Review of Doctoral (PhD) **Dissertation**

Reviewer: Prof. Dr. habil. Hosam Eldin Bayoumi CSc

Candidate (PhD student): Ali Dawood Salman

Title of Thesis: Utilization of the Bauxite residue to Recover Scandium Rare Earth Element

General description

Red mud contains various sources of elements in the category of major, minor, and rare earth elements. In the past 11 years, researchers have been more motivated towards the valuable recovery of metal ions from red mud as resources. Researchers have focused on various metals present in major and minor quantities in red mud and of which significant amounts could be removed using various processes, such as sintering and carbothermal smelting processes using metallurgical routes. The economic cost of red mud handling and use is one of the important issues associated with the bauxite industry. The amount of funds will increase by government and industry based on the capacity of alumina production. Nevertheless, it is highly beneficial to construct in-house facility for metal extraction that will reduce the expense of transportation of red mud to other location.

Red mud is one of the by-products generated in the aluminium industry from the ore of bauxite during the calcination process for the extraction of aluminium dioxide. The term "red mud" is established and derived from the two words of "red", which refers to the colour, and "mud", which refers to the waste generated after the alumina extraction from the bauxite ore, by a calcination process. Generally, 2.5–3 kg of red mud is produced in each 1 kg of Al production from the bauxite industry.

Although a lot of studies have been carried out on the recovery of metals, this step is still very limited to the laboratory scale. The lab-scale approach needs to be enhanced in commercial ways to recover metals from red mud as resources. The development of neutralization of red mud and the extraction of metals from red mud do require a good understanding of chemistry and the reduction process of red mud.

As the global production of aluminium is approximately 64 million tons, this result in 160 million tons of red mud to dispose of. The recovery of critical raw materials from red mud involves many benefits including environmental, social, financial, economic, and technological benefits. The

content of metals such as Ti, Si, Fe, Na, and Al in red mud is 2–12%, 1–9%, 14–45%, 1–6% and 5–14% respectively.

Red mud as a resource opens up various possibilities for the extraction of minerals and ions such as the major elements Fe, Ti, Mn, Al and Ca, Na, Si, Cr, Mn, V, La, Sc, Y. Rare earth elements (REE) such as Ce (102 mg/kg), La (56 mg/kg), Sc (47 mg/kg), Nd (45 mg/kg), Sm (9 mg/kg) are also valuable elements present inside red mud.

Red mud is a type of hazardous industrial waste, generated during the production of alumina from bauxite by Bayer technology, and has very complex components. The recovery of rare earth elements from this waste is of great importance to sustainable utilization and management of natural resources and environmental protection. In the present work, the researcher recovered scandium and iron from the real red mud by using new protocols based on organophosphorus compounds, and the results obtained are very remarkable. Research direction, approach, and results achieved show that this study is practical and meaningful, opening up promising possibilities in practice. Bauxite residue contains substantial concentrations of rare earth elements (REEs), but their recovery is a challenge. Nowadays, management of bauxite residue represents a major issue for the aluminium industry because of its high alkalinity and the large quantities produced annually.

The REEs are nowadays considered as strategic elements because of their importance for modern technology and clean-tech applications. The subject of REEs has become a hot industrial and strategic issue due to its core role in current and emerging technologies, particularly in light if their rarity. Among the REEs, scandium represents up to 90% of the economic value of the red mud. The most promising applications of scandium are solid oxide fuel cells and scandium-aluminium alloys. However, there are a number of other uses for the material.

A key point to benefit in terms of human resources and the economy could be the establishment of a plant for the beneficiation of red mud as resource alongside the bauxite industry. Particularly, to avoid transportation costs, the waste utilization facility processes and tools such as electric arc furnace, sintering of red mud, and leaching facility should be present in the proximal areas of the aluminium industry. One of the innovative processes in the production of pig iron is a by-product from reduced red mud by the carbothermal reduction process.

Finally, it can be used in the carbothermal reduction process for iron recovery, which could be a possible step for steel making. The rest of the residual red mud could be considered as the reductant for alumina recovery. Major use in the areas of construction and landfill opens the application of red mud in combination with metal recoveries such as Al, Fe, and its integrated combination towards the reduction process for the steelmaking. Integrating the red mud with other materials could improve its use in synergetic utilization.

A unique cost-effective and environmentally sustainable technique is very challenging to achieve. The recovery of metals and minerals from red mud using multiple different potential techniques need to be emphasized and implemented.

According to the literature, the recovery of Sc from the aqueous solution is generally performed by several techniques including solvent extraction (SX) or liquid-liquid extraction (LLE), ion

exchange (IX), liquid membrane (LM), adsorption, and precipitation. The researcher investigated most of these techniques, develop new promise solvent extraction protocols based on organophosphorus compounds, investigate for first time the possibility of extraction of Sc from model solution by specific macrocyclic compounds. Moreover, he synthesised of eco-friendly materials based on organophosphorus compounds for green separation without using organic solvents.

The Dissertation is summarized by the following concepts:

- The recovery of rare earth elements from this waste is of great importance to sustainable utilization and management of natural resources and environmental protection.
- In the present Dissertation, the candidate recovered **scandium** and **iron** from the real bauxite residue by using novel protocols / approaches based on organophosphorus compounds, and the results obtained are very remarkable.
- Bauxite residue contains substantial concentrations of rare earth elements, but their recovery is a challenge. Nowadays, management of bauxite residue represents a major issue for the aluminium industry because of its high alkalinity and the large quantities produced annually.
- It is very hard work were done, the candidate studied different separation technologies: Solvent extraction (organophosphorus or macrocyclic liquids), ion exchange, and solid phase extraction (organophosphorus compounds modified solid support).
- Research direction, approach, and results achieved show that this study is practical and meaningful, opening up promising possibilities in practice.
- Based on the outcomes of this study, there is a big hope to apply this technology in industrial scale to recover scandium element from Hungarian bauxite residue.
- The Dissertation is designed well distributed in 5 sections: introduction, literature, and the aim of the PhD research work in the first part of it. Then, the experimental part which is consisted of the materials and methodology, the conclusion, and finally, the new scientific thesis points are presented.
- The publication activity excellent, the researcher published in high level international journals with the impact factor between 1,7 and 9,9.
- The novelty and scientific results are clearly given in 3 major points (5.1., 5.2., and 5.3), with altogether 6 subpoints.

- The researcher employed the modern mathematical analysis science and statistical software's to processing his research results. This is outstanding, because the dissertation included huge experimental work and results.
- The publication list of the candidate indicates that he understands the problem of his research wok and had demonstrated how and by which method can be solved. The candidate has 7 out of 24 published articles as first author and he act as co-author in the rest of the list given all of them had high impact factor, which showed the significant of these publication to solve one the environmental problems.

Publications related to dissertation:

1. **Salman, A. D**.; Juzsakova, T.; Jalhoom, M. G.; Le Phuoc, C.; Mohsen, S.; Adnan Abdullah, T.; Zsirka, B.; Cretescu, I.; Domokos, E.; Stan, C. D., Novel hybrid nanoparticles: synthesis, functionalization, characterization, and their application in the uptake of scandium (III) ions from aqueous media. Materials, 2020, 13 (24), 5727.**IF= 3.7.**
2. **Salman, A. D**.; Juzsakova, T.; Ákos, R.; Ibrahim, R. I.; Al-Mayyahi, M. A.; Mohsen, S.; Abdullah, T. A.; Domokos, E., Synthesis and surface modification of magnetic Fe_3O_4@ SiO_2 core-shell nanoparticles and its application in uptake of scandium (III) ions from aqueous media. Environmental Science and Pollution Research 2021, 28 (22), 28428-28443. **IF= 5.1.**
3. **Salman, A. D**.; Juzsakova, T.; Rédey, Á.; Le, P.-C.; Nguyen, X. C.; Domokos, E.; Abdullah, T. A.; Vagvolgyi, V.; Chang, S. W.; Nguyen, D. D., Enhancing the Recovery of Rare Earth Elements from Red Mud. Chemical Engineering & Technology 2021, 44 (10), 1768-1774. **IF= 2.2**
4. **Salman, A. D**.; Juzsakova, T.; Jalhoom, M. G.; Abdullah, T. A.; Le, P.-C.; Viktor, S.; Domokos, E.; Nguyen, X. C.; La, D. D.; Nadda, A. K.; Nguyen, D. D., A selective hydrometallurgical method for scandium recovery from a real red mud leachate: A comparative study. EnvironmentalPollution, 2022, 308, 119596.**IF= 9.9.**
5. **Salman, A. D**.; Juzsakova, T.; Mohsen, S.; Abdullah, T. A.; Le, P.-C.; Sebestyen, V.; Sluser, B.; Cretescu, I., Scandium Recovery Methods from Mining, Metallurgical Extractive Industries, and Industrial Wastes. Materials 2022, 15 (7), 2376. **IF= 3.7.**
6. **Salman, A. D**.; Juzsakova, T.; Jalhoom, M.; Ibrahim, R.; Domokos, E.; Al-Mayyahi, M.; Abdullah, T.; Szabolcs, B.; Al-Nuzal, S., Studying the extraction of scandium (III) by macrocyclic compounds from aqueous solution using optimization technique. International Journal of Environmental Science and Technology, 2022, 1-18. **IF= 3.5.**
7. **Salman, A. D**.; Juzsakova, T.; Jalhoom, M. G.; Le, P.-C.; Abdullah, T. A.; Cretescu, I.; Domokos, E.; Nguyen, V.-H., Potential Application of Macrocyclic Compounds for

Selective Recovery of Rare Earth Scandium Elements from Aqueous Media. Journal of Sustainable Metallurgy, 2022. **IF= 3.**

Questions
After reviewing few scientific comments:

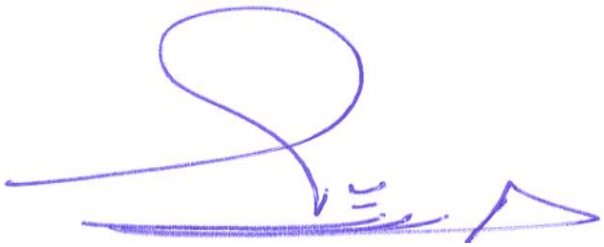
1. is it possible to recover Sc element from Hungarian bauxite residue in industrial scale?
2. Can you suggest some other economical elements to recover them from Hungarian bauxite residue?
3. As chemical engineer/ researcher, can you design/ suggest full flow sheet for the recovery of Sc from Hungarian bauxite residue based on Solid-Liquid Extraction?
4. You touched on a very important concept it's the selectivity and chelation of different compounds, explain what the difference between them?
5. Based on your experience, is it possible to apply one of the suggested methods on an industrial scale.

Final Conclusion

Utilization of the Bauxite residue to Recover Scandium Rare Earth Element Dissertation submitted for obtaining a PhD degree from the Doctoral School of Chemical Engineering and Material Science at the University of Pannonia in the branch of Bio, Environmental and Chemical Engineering Sciences written by Ali Dawood Salman fulfils all the conditions for gaining a PhD degree in chemical engineering and material science; therefore, it is recommended.

Finally, the PhD Dissertation reached the scientific level of the degree required.
Generally, the Dissertation is **scientifically accepted.**

Date: Budapest, 9th of May, 2023.



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