

EFFECT OF LEACHING REAGENT ON
LEACHING PROCESS OF EUROPIUM,
TERBIUM AND YTTRIUM FROM LIQUID
CRYSTAL DISPLAY

FAROUQ BIN AHMAT

Master of Science

UNIVERSITI MALAYSIA PAHANG



SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

(Supervisor's Signature)

Full Name : DR. MOHD YUSRI BIN MOHD YUNUS

Position : SENIOR LECTURER

Date :



STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations that have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

(Student's Signature)

Full Name : FAROUQ BIN AHMAT

ID Number : MKC13009

Date :

EFFECT OF LEACHING REAGENT ON LEACHING PROCESS OF EUROPIUM,
TERBIUM AND YTTRIUM FROM LIQUID CRYSTAL DISPLAY

FAROUQ BIN AHMAT

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Chemical & Natural Resources Engineering
UNIVERSITI MALAYSIA PAHANG

JANUARY 2019

ACKNOWLEDGEMENTS

Alhamdulillah, praise to Allah the most compassionate and merciful. First and foremost I would like to express my deepest gratitude to my supervisors, Dr. Mohd Yusri Mohd Yunus, Prof.Dato' Ir.Dr. Baddrulhisyam and Dr. Anwarrudin for their excellent guidance until completion of this research. I would like to thank Faculty of chemical engineering and natural resources (FKKSA) who let me experience the research of rare earth extraction in the field and practical issues beyond the textbooks, and financially supported my research. I would also like to thank to Central Lab UMP for their support in analyzing my research samples.

I would like to thank Assoc.Prof.Dr. Raihan Othman from International Islamic University Malaysia (IIUM) and Prof.Ir.Dr. Abu Bakar Mahat from Nilai University whom were always willing to help and give their best suggestions and priceless ideas. Thanks must also go to anyone who participated in this research and whose cooperation and input made this research possible

I wish to express my unqualified thanks to my parent and family. I could never have accomplish this thesis without their love, support, and understanding. Last but certainly not least, thanks to people and the government of Malaysia for financial support.

ABSTRAK

Paparan kristal cecair (LCD) monitor menggunakan penapis warna untuk menghasilkan gamut warna dan penapis ini terdiri daripada elemen europium (Eu), terbium (Tb) dan yttrium (Y). Kitar semula serta pemulihan semua elemen ini sangat penting kerana kekurangan elemen nadir bumi (REEs) dan juga kapasiti kelimpahan sisa elektronik (e-sisa), terutamanya monitor LCD yang tersedia di seluruh dunia. Kitar semula serta pemulihan semua elemen ini sangat penting kerana kekurangan REEs dan juga kapasiti kelimpahan sisa elektronik (e-sisa), terutamanya monitor LCD yang tersedia di seluruh dunia. Dalam hal ini, salah satu langkah penting dalam aktiviti pemulihan melibatkan proses larut-lesap. Oleh itu, kelakuan pelarutan unsur-unsur dalam larutan berair perlu difahami secara kritikal untuk menentukan urutan keutamaan REEs yang akan diekstrak dari sisa LCD. Kajian ini memberi tumpuan kepada proses pelaurtan Eu, Tb, dan Y dengan menggunakan asid hidroklorik (HCl), sulfurik (H_2SO_4) dan nitrik (HNO_3), di mana ia secara umum dibahagikan kepada dua bahagian utama. Bahagian pertama berkaitan dengan analisis sifat termodinamik, di mana gambarajah Pourbaix telah digunakan sebagai alat yang terutama mewakili kestabilan pelarutan. Keputusan menunjukkan bahawa Eu, Tb, dan Y larut dalam asid HCl, H_2SO_4 dan HNO_3 masing-masing sebagai kation individu dan membentuk kompleks samada dengan ligan dan radikal lain. Sementara itu, fasa kedua kajian ini berkenaan dengan keberkesanan pelarutan melalui ujian analisis berdasarkan dua mod eksperimen - satu dan dua peringkat proses pelarutan. Jumlah Eu, Tb, dan Y masing-masing diukur menggunakan teknik XRF dan ICP-MS. Namun demikian, teknik XRF tidak dapat mengesan sebarang REEs elemen kerana kepekatan REEs yang kecil berbanding dengan komposisi lain. Walau bagaimanapun, keputusan analisis ICP-MS menunjukkan bahawa hanya elemen Y yang dapat dilarut dengan baik sama ada oleh satu atau dua peringkat. Dua lagi unsur yang terdiri daripada Eu dan Tb, didapati dalam kuantiti yang sangat rendah dan sangat sukar untuk di ekstrak. Di samping itu, kedua-dua reagen HNO_3 dan H_2SO_4 dikenal pasti sebagai pilihan terbaik untuk digunakan sebagai reagen pelarutan berbanding dengan HCl. Analisis struktur morfologi terhadap sampel yang tersisa terutamanya selepas pelarutan menunjukkan bahawa morfologi sampel H_2SO_4 - HNO_3 dan HNO_3 - H_2SO_4 relatif tinggi dalam kepadatan. Ini mungkin disebabkan unsur-unsur silikon yang tidak larut semala proses pelarutan. Ia boleh dirumuskan bahawa hanya elemen Y yang boleh diekstrak daripada Eu atau Tb dari e-sisa LCD.

ABSTRACT

Liquid crystal display (LCD) monitor uses color filter to produce color gamut and this particular filter is mainly made up from europium (Eu), terbium (Tb) and yttrium (Y) of Rare Earth Elements (REEs). Recycling as well as recovering of all these elements are of particularly important due to the scarcity of REEs and also the abundance capacity of electronic waste (e-waste), especially LCD monitors that available worldwide. In this regard, one of the crucial steps in recovering activities is involving leaching process. Thus, the dissolution behavior of the elements in the aqueous solution needs to be critically understood in order to determine the priority sequence of the REEs that to be extracted from the LCD scraps. This study focuses on the dissolution process of Eu, Tb, and Y using hydrochloric (HCl), sulfuric (H₂SO₄) and nitric (HNO₃) acids respectively, whereby it is generally divided into two main parts. The first part relates to the thermodynamic property analysis, whereby Pourbaix diagram has been utilized as the tool in mainly representing the dissolution stability. The results showed that Eu, Tb, and Y are dissolved in HCl, H₂SO₄ and HNO₃ acids respectively as an individual cations and forming complex with ligand and other radical. Meanwhile, the second phase of the study deals with assessing the dissolution effectiveness via analytical testing, particularly based on two experimental modes – single and two stages of dissolution processes. Regarding this, the amount of Eu, Tb, and Y were measured respectively using XRF and ICP-MS techniques. Unfortunately, the XRF method was unable to detect any of the elements due to their very small REEs concentration relative to other compositions. However, the results of ICP-MS analysis have shown that only Y element was dissolvable feasibly either by single or two-stage steps. This observation also suggests that the other two elements, which consist of Eu and Tb, are extremely low in quantity and complicated to be recovered. In addition, both HNO₃ and H₂SO₄ solutions were identified as the best option to be utilized as the dissolution reagents relative to HCl. The morphology structure analysis on the remaining samples particularly after the dissolution completed indicates that the morphology of H₂SO₄-HNO₃ as well as HNO₃-H₂SO₄ samples are relatively richer in the molecules compactness. This is perhaps due to the silicon elements that did not dissolve effectively during the dissolution process. It can be summarized that only Y element is practically feasible to be extracted rather than Eu or Tb from the LCD e-waste.

TABLE OF CONTENT

DECLARATION	
TITLE PAGE	
ACKNOWLEDGEMENTS	ii
ABSTRAK	iii
ABSTRACT	iv
TABLE OF CONTENT	v
LIST OF FIGURES	xi
LIST OF SYMBOLS	xiv
LIST OF ABBREVIATIONS	xv
CHAPTER 1 INTRODUCTION	1
1.1 Research Background	1
1.2 Problem Statement	2
1.3 Research Objectives and Scope	4
1.4 Thesis Organization	4
CHAPTER 2 LITERATURE REVIEW	6
2.1 Rare Earth Elements Overview	6
2.2 Rare Earth Resources	7
2.2.1 Bastnasite	8
2.2.2 Monazite	8
2.2.3 Xenotime	9
2.2.4 Recycling Source of Rare Earth Elements	9
2.3 Main Rare Earth Element Producers	10

2.3.1	Molycorp	10
2.3.2	Malaysian Rare Earth Corporation	11
2.3.3	Asian Rare Earth	11
2.3.4	Indian Rare Earth	12
2.3.5	The Baotou Iron and Steel Company	12
2.3.6	Lynas Advance Material Plant	12
2.3.7	Narva light sources GmbH	13
2.3.8	Solvay-Rhodia	13
2.4	Price of Rare Earth Oxides	14
2.5	Rare Earth Elements as Critical Elements	15
2.6	Rare Earth Elements in the Liquid Crystal Display Waste	15
2.7	Europium	17
2.7.1	Properties	17
2.7.2	Occurrence	18
2.7.3	Application	18
2.8	Terbium	18
2.8.1	Properties	18
2.8.2	Occurrence	19
2.8.3	Application	19
2.9	Yttrium	19
2.9.1	Properties	19
2.9.2	Occurrence	20
2.9.3	Application	20
2.10	Liquid Crystal Display	20
2.10.1	Working Principle	21
2.10.2	Color Filter	21

2.11	Phosphor	22
2.11.1	Working principle	22
2.11.2	Tri-phosphor	23
2.11.3	Red-Emitting Phosphor	23
2.11.4	Blue Emitting Phosphor	24
2.11.5	Green Emitting Phosphor	24
2.12	Extraction Techniques of Rare Earth Elements	24
2.12.1	High-Temperature Process	24
2.12.2	Chlorination	25
2.12.3	Selective Oxidation	25
2.12.4	Selective Reduction	25
2.12.5	Fractional Crystallization	26
2.12.6	Fractional Precipitation	27
2.12.7	Ion Exchange	27
2.12.8	Solvent Extraction	28
2.13	Type of Reagent for Dissolution	30
2.13.1	Sulfuric Acid	31
2.13.2	Nitric Acid	33
2.13.3	Hydrochloric Acid	34
2.14	Pourbaix Diagram	35
2.15	Fundamental of Pourbaix Diagram	36
2.16	Application of Pourbaix Diagram	37
2.17	Limitation of the Pourbaix Diagram	38
2.18	HSC 6.0	38
2.19	Justification and Summary	39

CHAPTER 3 MATERIALS AND METHODS	40
3.1 Introduction	40
3.2 Research Materials	40
3.3 Method	41
3.3.1 Constructing Pourbaix Diagram	41
3.3.2 Dissolution process	43
3.3.3 Characterization	43
3.4 Characterization Techniques	44
3.4.1 Thermodynamic Analysis	44
3.4.2 X-Ray Fluorescence Spectroscopy (XRF)	44
3.4.3 Inductively Coupled Plasma Mass Spectrometer(ICP-MS)	45
3.4.4 Field Emission Scanning Electron Microscope (FE-SEM)	47
CHAPTER 4 RESULTS AND DISCUSSION	49
4.1 Introduction	49
4.2 Pourbaix Diagram for Rare Earth Element Systems	49
4.2.1 Hydrochloric Acid Dissolution Reagent	51
4.2.2 Sulfuric Acid Dissolution Reagent	52
4.2.3 Nitric Acid Dissolution Reagent	53
4.3 X-ray Fluorescence Spectroscopy (XRF) Result	54
4.4 Inductively Coupled Plasma Mass Spectrometry (ICP-MS) Results	55
4.5 Microstructure Morphology Analysis Using Field Emission Scanning Electron Microscopy (FE-SEM)	58

CHAPTER 5 CONCLUSION AND RECOMMENDATION	61
5.1 Conclusion	61
5.2 Recommendations	62
REFERENCES	63
APPENDIX A	70
APPENDIX B	71

LIST OF TABLES

Table 1.1	Commercial E-Waste Processing	2
Table 1.2	Luminescence Color	3
Table 1.3	Global Recycling Potentials for Rees From E-Waste	3
Table 2.1	Major REEs producers	10
Table 2.2	Prices of Individual Rare Earth Oxides	14
Table 2.3	Atomic Properties of Eu, Tb, and Y	16
Table 2.4	Thermal, Electrical and Magnetic Properties of Eu, Tb, and Y	16
Table 2.5	Physical and Chemical Properties of Sulfuric Acid	32
Table 2.6	Sulfuric Acid Grades	32
Table 2.7	Physical and Chemical Properties of Nitric Acid	33
Table 2.8	Nitric Acid Grades	34
Table 2.9	Physical And Chemical Properties of Hydrochloric Acid	35
Table 4.1	LCD Waste Composition (Raw Sample)	54
Table 4.2	Element Concentration in Raw Sample	57
Table 4.3	Y Concentration	57
Table 4.3	Dissolution Effectiveness	57

LIST OF FIGURES

Figure 2.1	Periodic Table	6
Figure 2.2	REEs Classification	7
Figure 2.3	LCD Schematic Diagram	20
Figure 2.4	Color Gamut	21
Figure 2.5	Emission Spectra for Blue (A), Green (B) and Red (C)	23
Figure 2.6	Typical Solvent Extraction Flowsheet	28
Figure 2.7	Pourbaix Diagram Quadrant	37
Figure 3.1	HSC 6.0 Screen	41
Figure 3.2	HSC Data Generation	42
Figure 3.3	HSC Generated Pourbaix Diagram	42
Figure 3.4	XRF Working Principle	45
Figure 3.5	ICP-MS Schematic Diagram	46
Figure 3.6	Incident Beam and Scatter Electron	47
Figure 4.1	FE-SEM Micrograph.(a) Raw Sample; (b) Treated with HCl; (c) Treated with HNO ₃ ; (d) Treated with H ₂ SO ₄	58
Figure 4.2	SiO ₂ Powder	59
Figure 4.3	FE-SEM Micrograph.(a) Treated with HCl-H ₂ SO ₄ ; (b) Treated with HCl-HNO ₃ ; (c) Treated with HNO ₃ -HCl; (d) Treated with HNO ₃ -H ₂ SO ₄ ; (e) Treated with H ₂ SO ₄ -HCl; (f) Treated with H ₂ SO ₄ -HNO ₃	59
Figure 6.1	Flowchart Scheme of Experiment	70
Figure 6.2	Pourbaix Diagram for Eu-Cl-H ₂ O System (Eu = 1.0 m, Cl = 1.0 m)	71
Figure 6.3	Pourbaix Diagram for Y-Cl-H ₂ O System (Y = 1.0 m, Cl = 1.0 m)	71

Figure 6.4	Pourbaix Diagram for Tb-Cl-H ₂ O System (Tb = 1.0 m, Cl = 1.0 m)	72
Figure 6.5	Pourbaix Diagram for Eu-Cl-H ₂ O System (Eu = 1.0 m, Cl = 0.1 m)	72
Figure 6.6	Pourbaix Diagram for Y-Cl-H ₂ O System (Y = 1.0 m, Cl = 0.1 m)	73
Figure 6.7	Pourbaix Diagram for Tb-Cl-H ₂ O System (Tb = 1.0 m, Cl = 0.1 m)	73
Figure 6.8	Pourbaix Diagram for Eu-Cl-H ₂ O System (Eu = 1.0 m, Cl = 3.0 m)	74
Figure 6.9	Pourbaix Diagram for Y-Cl-H ₂ O System (Y = 1.0 m, Cl = 3.0 m)	74
Figure 6.10	Pourbaix Diagram for Tb-Cl-H ₂ O System (Tb = 1.0 m, Cl = 3.0 m)	75
Figure 6.11	Pourbaix Diagram for Eu-S-H ₂ O System (Eu = 1.0 m, S = 1.0 m)	75
Figure 6.12	Pourbaix Diagram for Y-S-H ₂ O System (Y = 1.0 m, S = 1.0 m)	76
Figure 6.13	Pourbaix Diagram for Tb-S-H ₂ O System (Tb = 1.0 m, S = 1.0 m)	76
Figure 6.14	Pourbaix Diagram for Eu-S-H ₂ O System (Eu = 1.0 m, S = 0.1 m)	77
Figure 6.15	Pourbaix Diagram for Y-S-H ₂ O System (Y = 1.0 m, S = 0.1 m)	77
Figure 6.16	Pourbaix Diagram for Tb-S-H ₂ O System (Tb = 1.0 m, S = 0.1 m)	78
Figure 6.17	Pourbaix Diagram for Eu-S-H ₂ O System (Eu = 1.0 m, S = 3.0 m)	78
Figure 6.18	Pourbaix Diagram for Y-S-H ₂ O System (Y = 1.0 m, S = 3.0 m)	79
Figure 6.19	Pourbaix Diagram for Tb-S-H ₂ O System (Tb = 1.0 m, S = 3.0 m)	79
Figure 6.20	Pourbaix Diagram for Eu-N-H ₂ O System (Eu = 1.0 m, N = 1.0 m)	80
Figure 6.21	Pourbaix Diagram for Y-N-H ₂ O System (Y = 1.0 m, N = 1.0 m)	80
Figure 6.22	Pourbaix Diagram for Tb-N-H ₂ O System (Tb = 1.0 m, N = 1.0 m)	81
Figure 6.23	Pourbaix Diagram for Eu-N-H ₂ O System (Eu = 1.0 m, N = 0.1 m)	81
Figure 6.24	Pourbaix Diagram for Y-N-H ₂ O System (Y = 1.0 m, N = 0.1 m)	82
Figure 6.25	Pourbaix Diagram for Tb-N-H ₂ O System (Tb = 1.0 m, N = 0.1 m)	82

Figure 6.26	Pourbaix Diagram for Eu-N-H ₂ O System (Eu = 1.0 m, N = 3.0 m)	83
Figure 6.27	Pourbaix Diagram for Y-N-H ₂ O System (Y = 1.0 m, N= 3.0 m)	83
Figure 6.28	Pourbaix Diagram for Tb-N-H ₂ O System (Tb = 1.0 m, N= 3.0 m)	84

LIST OF SYMBOLS

%	Percentage
°C	Celcius
μ	Micro
aq	Aqueous
C _p	Heat capacity
e	Electron
E ⁰	Standard electrode potential
E _h	Activity of electron
g	Gas
g/cm ³	Density
g/mol	Molar mass
J/mol·K	Standard entropy
K	Kelvin
k	Reaction constant
K _{eq}	Equilibrium constant
kPa	Kilopascal
l	Liquid
ml	Milliliter
mmHg	Pressure
pH	Potential of hydrogen
R	Gas constant
s	Solid
T	Temperature
V	Voltage
ΔG	Gibbs free energy of formation

LIST OF ABBREVIATIONS

ARE	Asian Rare Earth
BCC	Body-Centered Cubic
BISC	The Baotou Iron And Steel Company
BSE	Backscattered Secondary Electron
CdS	Cadmium Sulphide
CRT	Cathode Ray Tube
DOE	Department Of Enviroment
DVB	Divinylbenzene Bridge
EDTA	Ethylene Diamine Tetra Acetate
FE-SEM	Field Emission Scanning Electron Microscopy
HEDTA	N-Hydroxyl Ethyethyldiaminetri Acetate
HREE	Heavy Rare Earth Element
HTP	High-Temperature Process
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
IRE	Indian Rare Earth
LAMP	Lynas Advance Material Plant
LCD	Liquid Crystal Display
LREE	Light Rare Earth Element
MAREC	Malaysian Rare Earth Corporation
NiMH	Nickel-Metal Hydride
PPB	Part Per Billion
PPM	Part Per Million
ppq	Part Per Quadrillion
R&D	Research And Development
RE	Rare Earth
REE	Rare Earth Element
REO	Rare Earth Oxide
RGB	Red, Green, and Blue
SE	Secondary Electron
TFT	Thin-Film Transistor
UV	Ultra-Violet

XRF

X-Ray Fluorescent

YAG

Yttrium-Aluminum-Garnet

REFERENCES

- Agilent. (2006). *Agilent 7500 Series ICP-MS*.
- Al-hinai, A. T., Al-hinai, M. H., & Dutta, J. (2014). Application of Eh-pH diagram for room temperature precipitation of zinc stannate microcubes in an aqueous media. *Materials Research Bulletin*, 49(April 2018), 645–650.
- Ashar, N., & Golwalkar, K. (2013). Processes of manufacture of sulfuric acid. In *A Practical Guide to the Manufacture of Sulfuric Acid* (pp. 9–30). Springer International Publishing Switzerland.
- Bamfield, P. (2001). *Chromic phenomena* (First). Bristol: The Royal Society of Chemistry.
- Bardal, E. (2004). *Corrosion and protection*. London: Springer-Verlag London Limited.
- Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., & Buchert, M. (2013). Recycling of rare earths: A critical review. *Journal of Cleaner Production*, 51, 1–22.
- Binnemans, K., Tom, P., Blanpain, B., & Gerven, T. Van. (2015). Towards zero-waste valorisation of rare-earth-containing industrial process residues : a critical review. *Journal of Cleaner Production*, 99, 17–38.
- Bruker. (2008). *Bruker model S8 Tiger catalogue*.
- Buchert, M. (2012). Recycling critical raw materials from waste electronic equipment Commissioned by the North Rhine- Westphalia State Agency for Nature , Environment and Consumer Protection Authors :, 49(0), 30–40.
- Cacace, J. E., & Mazza, G. (2003). Mass transfer process during extraction of phenolic compounds from milled berries, 59, 379–389.
- David, T., & James, T. (1998). *Corrosion science and technology*. Boca Raton: CRC Press LLC.
- Deqian, L. I. (2017). A review on yttrium solvent extraction chemistry and separation process. *Journal of Rare Earths*, 35(2), 107–119.

- Eduafo, P. M. (2016). *Investigation of recovery and recycling of rare earth elements from waste fluorescent lamp phosphors*. Colorado School of Mines.
- Ernst, W., & Markus, R. (2014). *Handbook of recycling: state of the art for practitioners, analysts, and scientists*. Amsterdam: Elsevier Inc.
- Frankenthal, R. P. (2002). *Corrosion science: A retrospective and current status in honor of Robert P. Frankenthal*. (G. . Frankel, H. . Issacs, J. . Scully, & J. . Sinclair, Eds.). Pennington: The Electrochemical Society, Inc.
- Guiñón, J. L. (2011). Pourbaix diagrams for titanium in concentrated aqueous lithium bromide solutions at 25 ° C, 53, 1440–1450.
- Gupta, C. K. K., & Krishnamurthy, N. (2005). *Extractive metallurgy of rare earths. International Materials Reviews* (Vol. 37).
- Hartley, F. R. (2007). The preparation of anhydrous lanthanon chlorides by high-temperature chlorination of monazite. *Journal of Applied Chemistry*, 2(1), 24–31.
- Hasegawa, H., Rahman, I. M. M., Egawa, Y., Sawai, H., Begum, Z. A., Maki, T., & Mizutani, S. (2013). Recovery of indium from end-of-life liquid-crystal display panels using aminopolycarboxylate chelants with the aid of mechanochemical treatment. *Microchemical Journal*, 106, 289–294.
- Havaux, D. (2014). *Photochemical recovery of europium from rare earth mixtures*.
- Haynes, W. . (2014). *CRC handbook of chemistry and physics* (95th ed.). CRC Press.
- Hosseini, Z., Heydari, S., & Rounaghi, G. H. (2016). The response behavior of PPy-DB18C6 electrode to terbium (III) in acetonitrile and its thermodynamic application. *Arabian Journal of Chemistry*, 9, S1110–S1116.
- Hui, X., Qiang, S., Zhongfu, A., Ying, W., & Xiaogang, L. (2015). Electroluminescence from europium(III) complexes. *Coordination Chemistry Reviews*, 293–294, 228–249.
- JEOL Ltd. (2017). *JSM-7800F catalogue*.
- Jha. (2014). *Rare earth materials* (First Edit). New York: CRC Press.
- Jha, M. K., Kumari, A., Panda, R., Rajesh Kumar, J., Yoo, K., & Lee, J. Y. (2016).

- Review on hydrometallurgical recovery of rare earth metals. *Hydrometallurgy*, 161, 77–101.
- Jordens, A., Cheng, Y. P., & Waters, K. E. (2013). A review of the beneficiation of rare earth element bearing minerals. *Minerals Engineering*, 41, 97–114.
- Kim, M. (2015). New display concept for realistic reproduction of high-luminance colors. *Displays*, 39, 117–124.
- King, M., Moats, M., & Davenport, W. (2013). *Sulfuric acid manufacture: Analysis, control and optimization* (Second Edi). San Diego: Elsevier.
- Kuan, S. H., Saw, L. H., & Yousef, G. (2016). A review of rare earths processing in Malaysia. In *Universiti Malaysia Terengganu International Annual Symposium on Sustainability Science and Management* (pp. 1–7).
- Kumar, P., & Bharadwaj, M. D. (2016). Rare earths recovery from secondary resources: Opportunities, challenges and environmental impacts (pp. 21–22).
- Landolt, D. (2007). *Corrosion and surface chemistry of metals*.
- Liu, S., Chen, L., & Gao, Y. (2013). Hexavalent chromium leaching influenced factors in the weathering chrome slag. *Procedia Environmental Sciences*, 18(0), 783–787.
- Machacek, E., Luth, J., Habib, K., & Klossek, P. (2015). Recycling of rare earths from fluorescent lamps : Value analysis of closing-the-loop under demand and supply uncertainties. “*Resources, Conservation & Recycling*,” 104, 76–93.
- McCoy, H. N. (1936). Contribution to the chemistry of europium. *Journal of the American Chemistry*, 58(9), 1577–1580.
- Merritt, R. R. (1990). High temperature methods for processing monazite: I. Reaction with calcium chloride and calcium carbonate. *Journal of the Less Common Metals*, 166(2), 197–210.
- Wan, M. (2015). *Understanding Japan-China relations: Theories and issues*. Singapore: World Scientific Publishing Co.Pte. Ltd.
- Morais, C. A., & Ciminelli, V. S. T. (2001). Recovery of europium by chemical reduction of a commercial solution of europium and Gadolinium chlorides. *Hydrometallurgy*, 60(3), 247–253.

- Myers, R. (2007). *The 100 Most Important Chemical Compounds: A Reference Guide* (First Edit). Westport: Greenwood Press.
- Nakamura, T., Nishihama, S., & Yoshizuka, K. (2007). Separation and recovery process. for rare earth metals from fluorescence material wastes using solvent extraction. *Solvent Extraction Research and Development*, 14, 105–113.
- Nasab, M. E., Sam, A., & Milani, S. A. (2011). Determination of optimum process conditions for the separation of thorium and rare earth elements by solvent extraction. *Hydrometallurgy*, 106(3–4), 141–147.
- Navrotsky, A., Lee, W., Mielewczyk-gryn, A., Ushakov, S. V, Anderko, A., Wu, H., & Riman, R. E. (2015). Thermodynamics of solid phases containing rare earth oxides. *The Journal of Chemical Thermodynamics*, 88, 126–141.
- Nikolaychuk, P. A. (2014). The third dimension in Pourbaix diagrams: A further extension. *Journal of Chemical Education*, 91(5), 763–765.
- Ochsenkiihn-Petropulu, M., Lyberopulu, T., Ochsenkiihn, K. M., & A, G. P. (1996). Recovery of lanthanides and yttrium from red mud by selective leaching aY. *Analytica Chimica Acta*, 319, 249–254.
- Park, H., & Rhee, S. (2016). Estimation of retorted phosphor powder from spent fluorescent lamps by thermal process. *Waste Management*, 50, 257–263.
- Paulick, H., & Machacek, E. (2017). The global rare earth element exploration boom : An analysis of resources outside of China and discussion of development perspectives. *Resources Policy*, 52(February), 134–153.
- Pawade, V. B., Swart, H. C., & Dhoble, S. J. (2015). Review of rare earth activated blue emission phosphors prepared by combustion synthesis. *Renewable and Sustainable Energy Reviews*, 52, 596–612.
- Poulsen, T. (2010). *Introduction to Chemistry*. C.K 12- Foundation.
- Pourbaix, M. (1974). *Atlas of electrochemical equilibria in aqueous solutions* (2nd ed.). Pergamon, New York: National Association of Corrosion Engineers.
- Ramesh, T., Somayajula, B., & Murthy, S. R. (2016). CoFe₂O₄-SiO₂ composites: Preparation and magnetodielectric properties. *Journal of Materials*, 2016(3), 1–7.

- Resende, L. V., & Morais, C. A. (2010). Study of the recovery of rare earth elements from computer monitor scraps – Leaching experiments. *Minerals Engineering*, 23(3), 277–280.
- Revie, W. (2011). *Uhlig's corrosion handbook* (Third). New York: Wiley.
- Revie, W., & Uhlig, H. (2008). *Corrosion and corrosion control: An introduction to corrosion science and engineering* (4th ed.). Hoboken: John Wiley & Sons, Inc.
- Ronda, C., & Jüstel, T. (1998). Rare earth phosphors fundamentals and applications. *Journal of Alloys and Compounds*, 275–277, 669–676.
- Rousseau, R. (2006). Corrections for matrix effects in X-ray fluorescence analysis — A tutorial, 61, 759–777.
- Rytz, D. (2010). Patent Application Publication (10) Pub. No.: US 2010/0177377 A1.
- Sahoo, S., Choudhary, R. N. P., Kumar, N., & Mathur, B. K. (2012). Ferroelectric properties and ac conductivity studies of yttrium modified Pb(Fe_{0.5}Nb_{0.5})O₃ ceramics. *Solid State Sciences*, 14(6), 668–672. Saito, T., Sato, H., & Motegi, T. (2006). Recovery of rare earths from sludges containing rare-earth elements. *Journal of Alloys and Compounds*, 425(1–2), 145–147.
- Schulze, R., & Buchert, M. (2016). Estimates of global REE recycling potentials from NdFeB magnet material. *Resources, Conservation & Recycling*, 113, 12–27.
- Sheir, L. L., Jarman, R. A., & G.T. Burstein (Eds.). (2000). *Corrosion control* (3rd Editio). Woburn: Butterworth-Heinemann.
- Skudžius, R., Enseling, D., Skapas, M., Selskis, A., Pomjakushina, E., Jüstel, T., ... Rüegg, C. (2016). Europium-enabled luminescent single crystal and bulk YAG and YGG for optical imaging. *Optical Materials*, 60, 467–473. <http://doi.org/10.1016/j.optmat.2016.08.032>
- So, H., Walawalkar, M., Nichol, C. K., & Azimi, G. (2016). Hydrometallurgy Process investigation of the acid leaching of rare earth elements from. *Hydrometallurgy*, 166, 195–204.
- Speight, J. G. (2002). *Chemical and Process Design Handbook*. New York: McGraw-

Hill.

Strauss, M. L. (2016). *The recovery of Rare earth oxides from waste fluorescent lamps*. Colorado School of Mines.

Taghizadeh, E., Mehdi, M., & Shiva, M. (2016). Determination of the thorium potential in Shah-Kooh area in Iran by NAA and comparison with the results of ICP and XRF techniques. *Measurement*, *90*, 20–24.

Thomas, R. (2004). *Practical guide to ICP-MS*. New York: Marcel Dekker Inc.

Vasconcellos, M. E. De, & Queiroz, C. A. S. (2004). Sequential separation of the yttrium — heavy rare earths by fractional hydroxide precipitation. *Journal of Alloys and Compounds*, *374*, 405–407.

Verink, E. D. (2000). *Simplified procedure for constructing Pourbaix diagrams* (Vol. 535).

Vijayalakshmi, R., Mishra, S. L., Singh, H., & Gupta, C. K. (2001). Processing of xenotime concentrate by sulphuric acid digestion and selective thorium precipitation for separation of rare earths. *Hydrometallurgy*, *61*(2), 75–80.

Wang, J., Xie, M., Wang, H., & Xu, S. (2017). Solvent extraction and separation of heavy rare earths from chloride (2 , 4 , 4 ' -trimethylpentyl) phosphinic acid. *Hydrometallurgy*, *167*, 39–47.

Wang, Z. L., & Zhou, W. (2006). *Scanning microscopy for nanotechnology*. Springer.

Wu, Y., Yin, X., Zhang, Q., Wang, W., & Mu, X. (2014). The recycling of rare earths from waste tricolor phosphors in fluorescent lamps : A review of processes and technologies. *Resources, Conservation & Recycling*, *88*(100), 21–31.

Xiang-yan, C., Xin-zhe, L., Qiu-li, Z., Hong-Zhou, M., & Jun, Z. (2009). Leaching vanadium by high concentration sulfuric acid from stone coal. *Transactions of Nonferrous Metals Society of China*, (20), 2–5.

Yang, J., Retegan, T., Steenari, B., & Ekberg, C. (2016). Recovery of indium and yttrium from Flat Panel Display waste using solvent extraction. *Separation and Purification Technology*, *166*, 117–124. Retrieved from

Yorukolu, A., & Girgin, I. (2002). Recovery of europium by electrochemical reduction from sulfate solutions. *Hydrometallurgy*, 63(1), 85–91.