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Economic potential assessment of neodymium recovery from Malaysia e-waste resource

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Abstract

Neodymium (Nd) is one of the core rare earth element (REE) which is in high demand globally and possesses huge economical advantage. However, Nd has been predicted to be in a great supply risk in the near future due to the dominant production and reserve controlled by China. Thus, the worldwide REE industry players nowadays look for alternative resources to further expand the scopes of REE supply. One of the potential sources is e-waste. Strengthening the recovery activity from e-waste streamlines could provide not only economically beneficial but more importantly may considerably lessening the environmental impact as a result of e-waste disposal. Hence, this study is proposed to study the economic potential assessment of recovering Nd which focusing on the Malaysia context. There are three Nd recovery processing models discussed - a) Nd extraction using P350 system b) Nd extraction using HDEHP-HCl system and c) Nd extraction using EHEHPA-HCl system. The analysis mainly highlights the amount of optimum economic gain by means of revenue index of each processing route as well as conducting cost-benefit analysis based on a set of specified investment performance targets of the selected processing. The results show that the P350 extraction system is the most feasible system with optimum revenue return for neodymium recovery of Malaysia from e-waste resource.

Selection and peer-review under responsibility of the scientific committee of the 6th International Conference on Recent Advances in Materials, Minerals & Environment (RAMM) 2018.

Keywords: E-waste; rare earth; neodymium

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1. Introduction

The demand for ‘Rare Earth Elements’ (REEs) from key industries such as electronics, mobile technology, renewable energy as well as defence sectors have exploded in the last decades. However, the extraction of REEs from its primary source is a challenging task. Since 1980s, China has dominated in the production and reserved mineral stock as compared to other countries. Thus, the competitiveness of global REE market is greatly depending on the trade policy of China [1].IIn this light, the world REE market can be perceived to be at the stake for all spectrums of REEs. In addressing the issue, various European countries and US has identified that certain components of REES such as Neodymium (Nd), Europium (Eu), Terbium (Tb), Dysprosium (Dy) and Yttrium (Y), may suffer from major supply restrictions in the near future [2]. This limitation could eventually induce huge spike in REEs price increments which was experienced back in the 2010-2012 period. If this prevails for a longer time, then sustaining the economic benefits of REEs-driven products is almost impossible. Hence, there is a need in recovering the REEs from alternative resources instead depending on the primary mining in order to sustain the critical global supply.

One of the sources is electronic waste (e-waste). E-waste is generally composed of all kinds of electrical or electronic goods which are at the end-of-life term consisting of permanent magnetic scrap, wind turbines, electric motors, generators, computers, TVs, and cell phones. Among of those, computers, televisions, and cell phones are some of the e-wastes which keep increasing radically over the years. In Malaysia, the cumulative total of e-waste that generated by the country in 2020 is expected to reach beyond 1,100 billion units [3]. E-waste in general is chemically and physically distinct from other forms of municipal or industrial waste; it contains both valuable and hazardous material, and thus, it requires special handling of material recovering as well as reducing environmental contamination and also detrimental effects on human health [4]. At present, commercial recycling of REEs is still extremely low. Despite a vast, mostly lab-scale research effort on REEs recycling, up to 2011 less than 1% of the REEs were actually recycled [1].

This paper discusses the preliminary work on the economic assessment of Nd recovery from the magnetic scrap resources of Malaysia. In particular, the main motive of the research is to determine the potential economic viability of processing route in recovering Nd that derived from the magnetic scrap by means of two options – using the existing extraction system or design a new recovery plant instead. The platform of the model assessment is developed using Microsoft Office Professional Plus Excel 2013 and the scopes are as follows:

- Analyzing as well as identifying the amount of e-waste category and its corresponding generation capacity for the years 2018-2020 from the inventory e-waste report of Malaysia [5].
- Developing the REEs solvent extraction (SX) sequence model and comparing the best revenue index based on three (3) separate sets of separation factor extractants.
- Determining the optimized parameter settings in terms of extraction factors of Neodymium extraction particularly for generating the maximum revenue index.

2. Extracting of REEs using Solvent Extraction System

In general, there are two categories of technologies available for REEs separation–hydrometallurgy and pyrometallurgy. The evaluation of Khaliq and his co-workers [6] on the two separation approaches suggest that hydrometallurgical method is more convenient on the dimension of accuracy, predictability and controllable rather than pyrometallurgy. They also commented that there were various successful studies have been conducted on the extraction of precious metals, copper, lead and zinc from e-waste using this separation route. In addition, Zhang et al. [7] reported that liquid-liquid SX system, which is one of the core techniques in the hydrometallurgical process, is perhaps the most dominant application for the recent commercial technology of REEs extraction.

2.1. Cascade Solvent Extraction Principles and Separation Pathway

The basic principle of any hydrometallurgical approach, including the SX system technique, involves dissolving the targeted mixed product in strong mineral acids for the purpose of precipitation to obtain the desired individual element based on a specified purity and recovery. In continuous operation, the SX system includes three separate phases–extraction, washing and stripping [7]. The target purity of the individual element can be practically achieved by multiple stages, and it is also known as cascade SX system.The cascade system works based on the mechanism of counter-current flow, where the aqueous (mixed product) and organic solutions (extractant) flow in opposite directions to each other, as well as involving several processing steps. In each of the extraction steps, chemical interaction between aqueous and organic solution take place and simultaneously producing the pregnant organic solution, which enriched with the targeted individual element that following specific purity level as desired.

Another critical factor is the selection of separation pathway as well as its corresponding extractant. The most widely used processing route of REEs of the primary mining resource is proposed by Mackowski [8] and summarized as 'The Art vs Science' structure (AvsS). As reported by Mackowski, the separation of REEs started with extracting the whole bulk of light elements of REEs (HREEs) from the heavy components of REEs (HREE). Later, the individual separation of REEs is executed following the corresponding groups accordingly. Yunus et al. [9] have transformed that particular structure into a table format as shown in Table 1. In their work, they have proposed a hybrid application model that utilizing two sets of extractants in order to maximize the economic potential return of the selected separation route. They have also proposed the term 'Separation Index (SI)' as the main basis in critically deciding which separation pathway that must be chosen such that the economic advantage is the highest (based on the specific type of extractant). The term SI is define as the scale factor which is derived based on the separation factor value and REE specific characterization divide by the number of extraction stage for that particular metal-extractant. In general, the separation pathway of REEs can be practically conducted based on three distinct approaches:

i. Mineral preference – the separation pathway is designed in such a way it extracts the major REEs components which have relatively higher concentration.
ii. Profit preference – the separation is executed on the element which contains attractive prices only.
iii. Separation factor (SF) preference – the separation is developed based on the ranking of SF complexity of the selected extractant. In other words, those elements which easily to be extracted (high SF value) have to be separated at the initial stage prior to other elements (low SF value).

Table 1: Individual REEs Extraction Step based on 'Art vs Science' Structure

STEP 1	**STEP 2**	**STEP 3**
1: Separation of LREE+HREE from the raw mat (Ce,La,Pr,Nd,**Sm,Eu,Gd,Dy,Ho-Lu)**	2: Separation of LREE from HREE (**Sm,Eu,Gd**,Dy,Ho-Lu)	3: Separation of Nd/Pr from Ce-La (La,Ce,**Pr,Nd)**
	2a : Extraction of Gd from Sm,Eu (Sm,Eu,**Gd)**	3a: Extraction of Pr from Nd (**Pr**,Nd)
	2b :Extraction of Eu from Sm (Sm,**Eu)**	3b: Extraction of Ce from La (**Ce**,La)
	2c: Extraction of Y from Tb-Lu (**Y**,Tb-Lu)	
	2d : Extraction of Dy from Tb,Ho-Lu (**Dy**,Tb,Ho-Lu)	

2.2. Cascade Solvent Extraction Model

In any of SX extraction systems, the basic separation mechanism is always taking place in the form of between two distinct elements or group of elements, which typically represented by 'A' (relatively easier to extract) and 'B' (relatively difficult to extract). There are two approaches of cascade SX models are discussed in Zhang et al. [7]. The first relates to extracting of Lanthanum and Praseodymium (La-Pr) mixture using P350 solution as the main organic extractant, where 'A' refers to Pr while B is La. The system performs separation of La-Pr with the presence of salting-out agent, with the specified separation factor $\beta_{Pr/La}$=5.0. By manipulating the organic/aqueous flow ratio, *R*, the extraction factors of La and Pr can be controlled to E_A=E_{Pr}=2.5 and E_B=E_{La}=0.5 respectively. The feed composition of La and Pr is fixed at 50% each. The stage efficiency is taken as 90% and hence the effective number of stages is 9 with the total number of stages is 10.

The detail formulation on calculating the purity, concentrating factor and recovery yield is comprehensively explained in by Zhang et al. [7]. From the calculation, it turns out that the recovery of Y_{La} is merely 50% while the corresponding purity has reached almost 100%. In order to increase the recovery yield of La up to 90%, E_{La} value has to be reduced to 0.1, which causing the scale of Φ_{La} increased proportionally. This will then affect Y_{La} to grow and settled around 90%. Nonetheless, this manipulation has compromised slightly the purity of La where the estimated final concentration is 97.16% with the same number of stages. While this can be fully accepted, the major damaging implication can be seen on the recovery of Pr. Reducing E_{La} has also caused E_{Pr} to be lowered at the same time. This will then suppress the Y_{Pr} recovery down to merely 50%. From this observation, it is clear that the purity and recovery of *A* and *B* elements are highly dependent on the magnitude as well as the manipulation of extraction and concentrating factors simultaneously.

In the second approach of SX model, however, Zhang et al. [7] have developed a systematic procedure to determine the number of stages that required to generate higher recovery as well as purity of REEs separation. In contrast to the first approach, the scale of both purity and recovery of the targeted REE are to be specified as the input values in the model. Normally, the purity is fixed at least 99.99% while the product recovery is set to be 90% at the minimum. In this regard, Yunus et al. [9], proposed a systematic procedure on calculating the estimate of SF values that derived from more than one component or involving separation between two groups of REEs components as shown in Eq. (1).

$$\beta_{A/B} = \frac{\Sigma\beta_i}{n-1} \tag{1}$$

Whereby, $\beta_{\mathrm{A/B}}$ is referring to the separation factor of either element A or B, $\Sigma\beta_{\mathrm{i}}$ is the SF summation of all individual REE (i) and n is indicated as number of REEs involving in that particular extraction. The concentrating factors for *A* and *B* are calculated using Eq. (2) and Eq. (3) respectively.

$$a = [\frac{P_A}{(1-P_A)}] / (\frac{f_A}{f_B}) \tag{2}$$

$$b=(a- Y_A)/ [a(1-Y_A)] \tag{3}$$

Whereby, f_{a} = mole fraction of *A* in feed, f_{b} = mole fraction of *B* in feed, P_{A} = purity of product *A* (organic phase), P_{B} = purity of product *B* (aqueous phase), Y_{A} = recovery of A and Y_{B} = recovery of B.

The corresponding extraction factors based on extraction (E_{M}) and scrubbing (E'_{M}) phases are provided based on Eq. (4) and Eq. (5) respectively:

$$E_M = \frac{1}{(\beta)^{0.5}} \tag{4}$$

$$E'_M = \frac{E_M \, x \, f'_B}{E_M \, x \, f'_A} \tag{5}$$

Finally, the estimated number of stages in extraction (n) and scrubbing (m) that required can be calculated using the following equations, Eq. (6) and Eq. (7) respectively:

$$n = \frac{\log b}{\log(\beta)(\frac{1}{E'_M})} \tag{6}$$

$$m = \frac{\log a}{\log(\beta)(\frac{1}{E'_m})} - 1 \tag{7}$$

Thus, the total number of stages, $t = n + m$ (8)

2.3. Inventory Survey of Malaysia's E-waste and REEs Composition

In 2009, Department of Environment, (DOE) Malaysia has conducted an e-waste inventory project which aimed to determine the e-waste flow pattern as well as its corresponding recycling activities based on Malaysia scenario [5]. Among of the key outputs of the survey, perhaps the most significant result is on the identification and prediction of the total e-waste generation from 1981 until 2020. In 2018 the amount of e-waste predicted was 18,231,000 units, 19,745,000 units in 2019 and 20,237,000 units in 2020. This study assumes that each of these PCs contained at least one set of a hard disk drive (HDD). It is from these HDDs that the component of Nd is obtained by means of scraped magnet. Meanwhile, Cucchiella et al. have established a comprehensive reference of material composition for various types of e-waste including HDD [10]. The generation of e-waste based on pc for selected REE as follows; Dysprosium (0.060 g/unit), neodymium (1 g/unit) and praseodymium (0.145 g/unit).

Despite the overall concentration of all REEs is relatively small, the capacity of e-waste generation in Malaysia is rather huge, and thus, the potential amount of alternative raw material resources is available [5]. In addition, the price of REEs in general as well as Nd in particular is considered high, for instance, the average price of Nd in the years 2015-2018 is around 70 USD per kg [10].

In this light, the production recovery of rare earth component *'i'* (C_i, in metric tonnes) and its corresponding economic revenue (Rev_i, in USD) can be estimated via Eq. (9) and Eq. (10) respectively.

$$C_i = K_i \times W \tag{9}$$

$$Rev_i = C_i \times P_i \tag{10}$$

Whereby, K_i = composition of rare earth component *'i'*, W= total amount of e-waste generation for that particular year and P_i= the rare earth component *'i'* price.

3. SX Modelling

This section describes the procedures of developing the Nd SX extraction model as well as the corresponding economic assessment. The general framework of this study is summarized as in Fig. 1. The constraints of this study are shown as follows:

1. Assumptions of Xu's cascade extraction principle based on Zhang et al. [7] as well as Xu et al. [11] are applied. There are five assumptions as listed below:
   a. Rare earth elements are represented by A, B, C
   b. The average separation factor $\beta_{A/B}$ is used.
   c. The rare earth concentration in the organic phase in each stage to be as close as possible.
   d. The aqueous feed and aqueous phase in the feeding stage have the same rare earth composition.
   e. The extraction stages and the scrubbing stages all have constant organic flow to aqueous flow ratios.
2. The impact of impurities of other elements excluding REEs are negligible and not interfering the REEs extraction efficiency.
3. All e-waste resources are assumed to have undergone effective dismantling and leaching procedures prior to SX stage.
4. The prices of REEs are subject to change.
5. There is no specific standard to fix the investment target, it all depends on the individual preference.
6. All calculations are performed based on Microsoft Office Professional Plus Excel 2013 platform.

From Fig. 1, all the analyses are conducted according to the individual year progress respectively (2018-2020). In the first (1st) step, the main task involves identifying the capacity of potential Nd recovery that generated from the e-waste stream of Malaysia for the years 2018-2020. In principle, the related calculations correspond to the Eq. (9) and Eq. (10) previously. The DOE, 2009 database is utilized as the main reference for e-waste generation in Malaysia. In particular, only the PCs scrap are considered in the analysis due to the potential amount of Nd element to be recovered is considered high. From Cucchiella et al. [10] other sources of e-wastes can also be taken into account (such as laptops, smart phone and tablets) but that information is not reported in DOE, 2009.

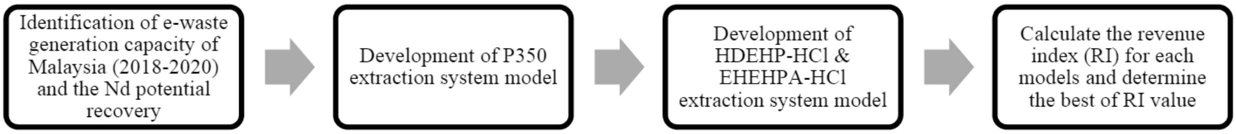


Fig. 1. The General Framework of SX Model and Economic Potential Assessment for Nd Extraction

The second (2nd) step relates on developing the SX model in separating Nd based on two main extraction phases. The first phase involves separating Dy from the mixtures of Nd-Pr, while the second phase performs separating Nd from Pr. In the context of P350 extractant system, Dy and Nd are considered to be an element of '*A*' in the each of the separation phases, respectively. This study perceives P350 system as the full recovery REEs process which has been fully operated and does not need any new investment in developing a new one. However, the purity and recovery of Nd might slightly compromised as the settings are not originally based on the Nd specifications (it was designed primarily to separate La-Pr mixture as discussed previously in section 2.1). Nonetheless, the purity of Nd is set to achieve 90% at a minimum and treated to be as the controlled variable. Finally, the amount of economic revenue is obtained based on the corresponding rate of recovery that calculated by the P350 SX model.

In contrast to the second step, the third (3rd) step deals with developing a new Nd SX model in order to get a good grade of purity and recovery rate of Nd. In this regard, two types of extractants are employed; Di-(2-ethylhexyl)phosphoric acid in hydrochloric acid medium (HDEHP-HCl) [7] and 2-ethylexyl phosphonic acid mono 2-ethylexhyl ester in hydrochloric medium (EHEHPA-HCl) [12] systems. All the procedures from Eq. (1)–(8) are utilized particularly to obtain the number of steps that required is separating Nd to achieve the desired purity and recovery rate of Nd. The purity of Nd is originally set to achieve 99.99%, while the recovery rate is specified to meet at least 90% minimum (both parameters are controlled at the initial stage). At the end, the amount of economic revenue is calculated for both recoveries (two different extractants are utilized) and it is expected both values to be close to the price that calculated from the first step but higher than that of the second step.

The fourth (4th) step corresponds to determine the revenue index (*RI*) for both P350 (second step) and the new SX model (third step) using Eq. (11).

$$RI = RV/n \tag{11}$$

4. Result and Discussion

4.1 Potential Capacity of Nd Recovery from Scrap Magnet

Table 2 shows the potential amount of Nd recovery that extracted from the Malaysia HDD scrap obtained from the inventory database for the years 2018-2020. Each of the capacities was calculated based on collection rate of 50%. From Table 2, it is clearly observed that Nd dominates in terms of composition more than 80% compared to other REEs. Regardless of the year, the overall compositions of Nd-Pr-Dy mixture from the scrapped HDD follows 83%-12%-5% respectively. Despite that, the prices of Nd is the lowest among of three (on average: Nd-USD 70/kg; Pr-USD124/kg; Dy-USD 281/kg) but the total economic revenue recovery of Nd alone can exceed USD 500,000, whereas the other two REEs are merely producing below than USD 200,000. In this regard, Nd should be treated as the major REEs that to be extracted primarily throughout 2018-2020.

Table 2. Potential Recovery Capacity of Nd from Malaysia HDD E-waste

Year	Weight (kg)		
	Nd	Pr	Dy
2018	8468	1228	508
2019	9171	1330	521
2020	9416	1365	565

4.1 *Extraction of Nd from Nd-Pr-Dy Mixture using P350 System*

Table 3 summarizes the whole results of extracting Nd from the mixture of Nd-Pr-Dy based on P350 system. In the first step, the results indicate that the SX P350 model can generate purity of Dy from Nd-Pr mixture at a relatively high concentration (97%) as well as retain the recovery capacity at 90% rate. In the second step, the recovery of Nd also produces around 90% rate, however the grade purity of Nd that recovered greatly lowered to merely 90% (this will affect on the original pricing).

Table 4 highlights the total economic revenue of Nd and Dy based on P350 system. From Table 4, despite that the unit price of Dy is higher than that of Nd, but the total annual revenue of Nd is found significantly larger in relative to Dy, whereby Nd and Dy have been extracted based on twenty and ten separation stages, respectively. The revenue index from Table 2 also suggests that it is advantageous to focus on the Nd recovery alone (higher *RI* value) rather than extracting both Nd and Dy together (where the integrated *RI* value for Nd-Dy is slightly increased). The same trend is also observed for 2019 and 2020 analyses.

Table 3. Results of Nd Extraction based on P350 System

Step 1: Extraction of Dy from Nd-Pr		**Step 2: Extraction of Nd from Pr-Nd**	
Characteristics	Calculated values	Characteristics	Calculated values
S.F. β_{Dy}	4.43	S.F. β_{Nd}	1.93
S.F. $\beta_{Dy/Nd}$	3.18	S.F. β_{Pr}	1.93
$A_{F(a)}$, Feed	4.98%	$A_{F(a)}$, Feed	13%
$B_{F(a)}$, Feed	95.02%	$B_{F(a)}$, Feed	87%
$E_{Dy} = E_{A,}$ extraction factor of Dy	2.215	$E_{Pr} = E_{A,}$ extraction factor of Nd	0.193
$E_{Pr/Nd} = E_{B,}$ extraction factor of Pr-Nd	0.5	$E_{Nd} = E_{B,}$ extraction factor of Pr	0.10
Stage efficiency	90%	Stage efficiency	90%
n, effective stages	9	n, effective stages	9
P_{Dy}, purity of Dy	97%	P_{Nd}, purity of Nd	90%
Y_{Dy}, recovery of Dy	90%	Y_{Nd}, recovery of Nd	90%

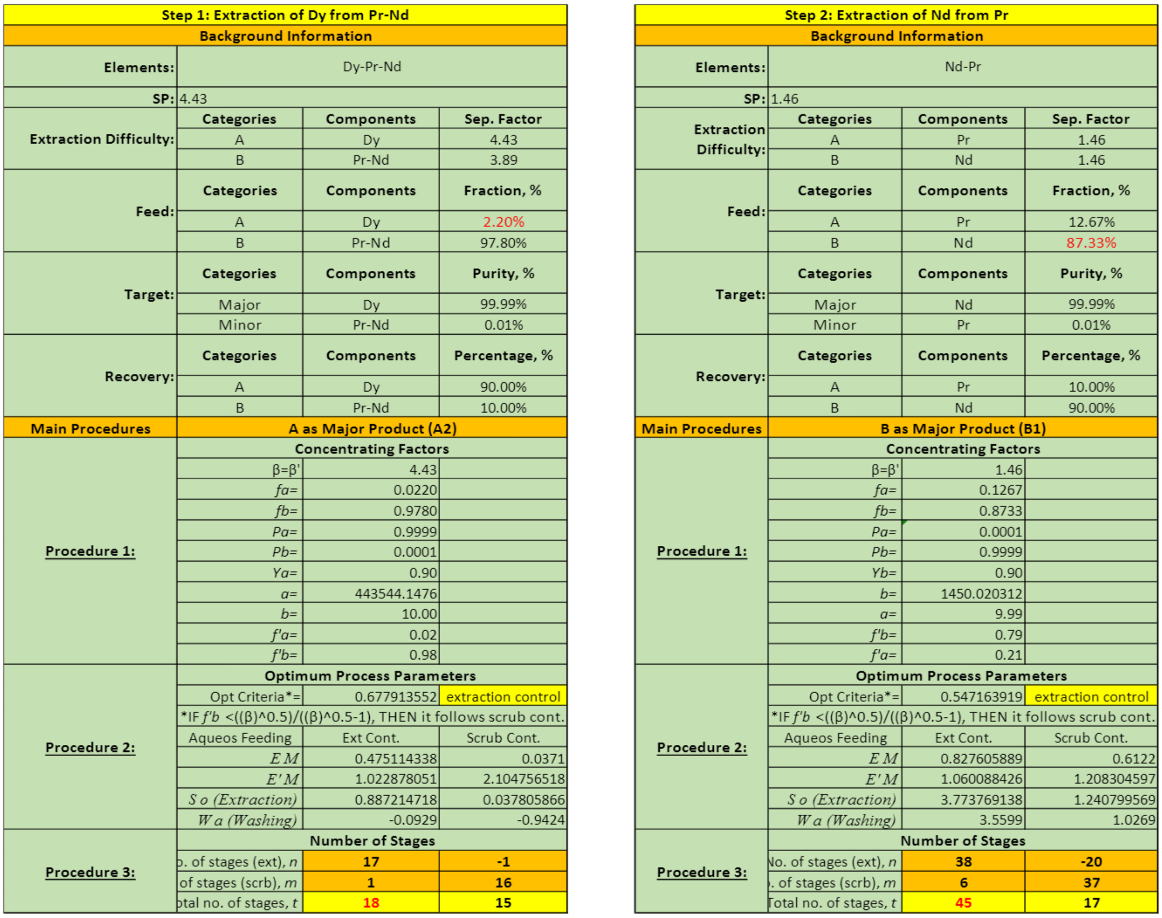
4.2 *Extraction of Nd from Nd-Pr-Dy Mixture using HDEHP-HCl & EHEHPA-HCl Systems*

Fig. 2 and 3 denote the results of extracting Nd from e-waste resource by applying extractants HDEHP-HCl (Ext I) & EHEHPA-HCl (Ext II) respectively. From both figures, it is clearly shown that the target purity and recovery rate are fixed to be at 99.99% and 90% respectively at the initial stage. Unlike to the previous approach, the motive of adopting Ext I and II is to gain the highest purity as well as recovery rate possible by adjusting the number of separation stages. In general, Ext I and II require around 63 and 52 stages in total respectively in order to meet the specified targets. These stages are extraordinarily huge compared to the P350 system previously.

Table 4. The Total Economic Revenue and Revenue Index of Nd Recovery based on P350 Model

Particulars	**REEs**		
	Nd	**Dy**	**Nd & Dy**
Price (USD/kg)*	63	281	-
Annual Revenue (USD)	388,910	27,994	416,903
Revenue Index	19,445	2,799	20,845

* Based on average price

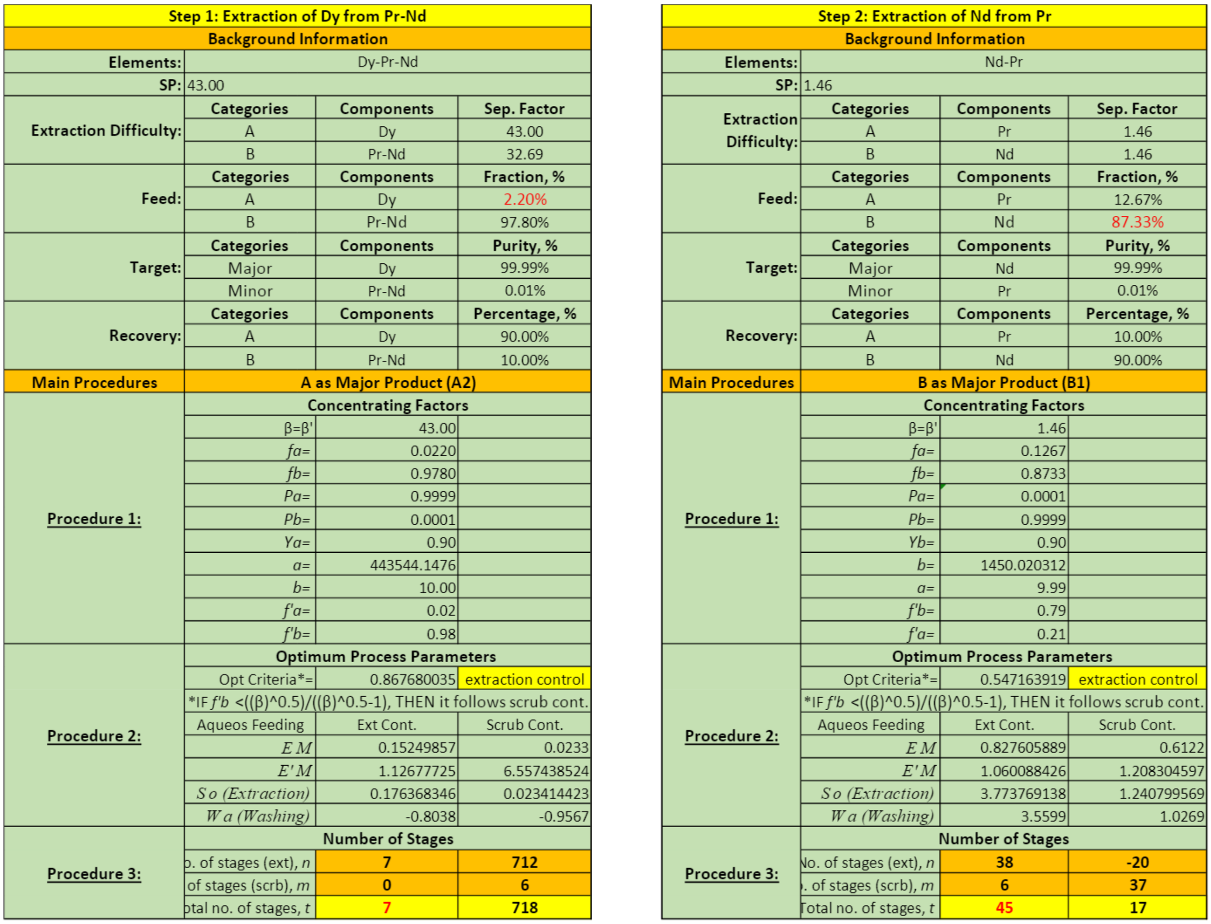


Step 1: Extraction of Dy from Pr-Nd			
Background Information			
Elements:	Dy-Pr-Nd		
SP:	4.43		
Extraction Difficulty:	**Categories**	**Components**	**Sep. Factor**
	A	Dy	4.43
	B	Pr-Nd	3.89
Feed:	**Categories**	**Components**	**Fraction, %**
	A	Dy	2.20%
	B	Pr-Nd	97.80%
Target:	**Categories**	**Components**	**Purity, %**
	Major	Dy	99.99%
	Minor	Pr-Nd	0.01%
Recovery:	**Categories**	**Components**	**Percentage, %**
	A	Dy	90.00%
	B	Pr-Nd	10.00%
Main Procedures	**A as Major Product (A2)**		
Procedure 1:	**Concentrating Factors**		
	β=β'	4.43	
	fa=	0.0220	
	fb=	0.9780	
	Pa=	0.9999	
	Pb=	0.0001	
	Ya=	0.90	
	a=	443544.1476	
	b=	10.00	
	f'a=	0.02	
	f'b=	0.98	
Procedure 2:	**Optimum Process Parameters**		
	Opt Criteria*=	0.677913552	extraction control
	*IF *f'b* <((β)^0.5)/((β)^0.5-1), THEN it follows scrub cont.		
	Aqueos Feeding	Ext Cont.	Scrub Cont.
	E M	0.475114338	0.0371
	E' M	1.022878051	2.104756518
	S o (Extraction)	0.887214718	0.037805866
	W a (Washing)	-0.0929	-0.9424
Procedure 3:	**Number of Stages**		
	o. of stages (ext), *n*	**17**	**-1**
	of stages (scrb), *m*	**1**	**16**
	tal no. of stages, *t*	**18**	**15**

Step 2: Extraction of Nd from Pr			
Background Information			
Elements:	Nd-Pr		
SP:	1.46		
Extraction Difficulty:	**Categories**	**Components**	**Sep. Factor**
	A	Pr	1.46
	B	Nd	1.46
Feed:	**Categories**	**Components**	**Fraction, %**
	A	Pr	12.67%
	B	Nd	87.33%
Target:	**Categories**	**Components**	**Purity, %**
	Major	Nd	99.99%
	Minor	Pr	0.01%
Recovery:	**Categories**	**Components**	**Percentage, %**
	A	Pr	10.00%
	B	Nd	90.00%
Main Procedures	**B as Major Product (B1)**		
Procedure 1:	**Concentrating Factors**		
	β=β'	1.46	
	fa=	0.1267	
	fb=	0.8733	
	Pa=	0.0001	
	Pb=	0.9999	
	Yb=	0.90	
	b=	1450.020312	
	a=	9.99	
	f'b=	0.79	
	f'a=	0.21	
Procedure 2:	**Optimum Process Parameters**		
	Opt Criteria*=	0.547163919	extraction control
	*IF *f'b* <((β)^0.5)/((β)^0.5-1), THEN it follows scrub cont.		
	Aqueos Feeding	Ext Cont.	Scrub Cont.
	E M	0.827605889	0.6122
	E' M	1.060088426	1.208304597
	S o (Extraction)	3.773769138	1.240799569
	W a (Washing)	3.5599	1.0269
Procedure 3:	**Number of Stages**		
	No. of stages (ext), *n*	**38**	**-20**
	. of stages (scrb), *m*	**6**	**37**
	Total no. of stages, *t*	**45**	**17**

Fig. 2. SX Model of Nd Recovery using HDEHP-HCl (Ext I) System

Meanwhile, Table 5 indicates the results of annual revenue as well as revenue index based on Nd SX model for Ext I and II, respectively. From Table 5, the total annual revenue for both extractants are found similar as both have managed to recover Nd at the same purity as well as recovery rate. However, the revenue index of Ext II is found slightly higher than that of Ext I. This is due to the fact that the number of stages of Ext II model is lesser in relation to Ext I. This can be clearly seen on step 1 separation (separating Dy from Pr-Nd) where Ext II only requires 7 steps, whereas its competitor needs to perform 18 stages in order to satisfy the same desired extraction target. In particular, Ext II naturally has ten times larger of separation factor value (43.00) compared to Ext I (4.43), and thus, it makes the extraction of Dy using Ext II is relative easier than Ext I.



Step 1: Extraction of Dy from Pr-Nd			
Background Information			
Elements:	Dy-Pr-Nd		
SP:	43.00		
Extraction Difficulty:	**Categories**	**Components**	**Sep. Factor**
	A	Dy	43.00
	B	Pr-Nd	32.69
Feed:	**Categories**	**Components**	**Fraction, %**
	A	Dy	2.20%
	B	Pr-Nd	97.80%
Target:	**Categories**	**Components**	**Purity, %**
	Major	Dy	99.99%
	Minor	Pr-Nd	0.01%
Recovery:	**Categories**	**Components**	**Percentage, %**
	A	Dy	90.00%
	B	Pr-Nd	10.00%
Main Procedures	**A as Major Product (A2)**		
Procedure 1:	**Concentrating Factors**		
	β=β'	43.00	
	fa=	0.0220	
	fb=	0.9780	
	Pa=	0.9999	
	Pb=	0.0001	
	Ya=	0.90	
	a=	443544.1476	
	b=	10.00	
	$f'a$=	0.02	
	$f'b$=	0.98	
Procedure 2:	**Optimum Process Parameters**		
	Opt Criteria*=	0.867680035	extraction control
	*IF $f'b$ <((β)^0.5)/((β)^0.5-1), THEN it follows scrub cont.		
	Aqueos Feeding	Ext Cont.	Scrub Cont.
	$E\,M$	0.15249857	0.0233
	$E'M$	1.12677725	6.557438524
	$S\,o$ (Extraction)	0.176368346	0.023414423
	$W\,a$ (Washing)	-0.8038	-0.9567
Procedure 3:	**Number of Stages**		
	o. of stages (ext), n	**7**	**712**
	of stages (scrb), m	**0**	**6**
	otal no. of stages, t	**7**	**718**

Step 2: Extraction of Nd from Pr			
Background Information			
Elements:	Nd-Pr		
SP:	1.46		
Extraction Difficulty:	**Categories**	**Components**	**Sep. Factor**
	A	Pr	1.46
	B	Nd	1.46
Feed:	**Categories**	**Components**	**Fraction, %**
	A	Pr	12.67%
	B	Nd	87.33%
Target:	**Categories**	**Components**	**Purity, %**
	Major	Nd	99.99%
	Minor	Pr	0.01%
Recovery:	**Categories**	**Components**	**Percentage, %**
	A	Pr	10.00%
	B	Nd	90.00%
Main Procedures	**B as Major Product (B1)**		
Procedure 1:	**Concentrating Factors**		
	β=β'	1.46	
	fa=	0.1267	
	fb=	0.8733	
	Pa=	0.0001	
	Pb=	0.9999	
	Yb=	0.90	
	b=	1450.020312	
	a=	9.99	
	$f'b$=	0.79	
	$f'a$=	0.21	
Procedure 2:	**Optimum Process Parameters**		
	Opt Criteria*=	0.547163919	extraction control
	*IF $f'b$ <((β)^0.5)/((β)^0.5-1), THEN it follows scrub cont.		
	Aqueos Feeding	Ext Cont.	Scrub Cont.
	$E\,M$	0.827605889	0.6122
	$E'M$	1.060088426	1.208304597
	$S\,o$ (Extraction)	3.773769138	1.240799569
	$W\,a$ (Washing)	3.5599	1.0269
Procedure 3:	**Number of Stages**		
	No. of stages (ext), n	**38**	**-20**
	. of stages (scrb), m	**6**	**37**
	Total no. of stages, t	**45**	**17**

Fig. 3. SX Model of Nd Recovery using EHEHPA-HCl (Ext II) System

In comparison to the P350 results, the revenue index of Nd recovery using both Ext I (7,292 USD/stage) or Ext II (8,930 USD/stage) is found in a great reduction in contra to P350 (19,455 USD/stage). This observation suggests that every stage that performed by P350 is producing more especially on the economic return as opposed to Ext I or II. Despite that the total revenue of both Ext I (USD 533,484) and Ext II (USD 533,484) is somewhat higher than that of P350 (USD 388,910) but the discrepancy in terms of revenue is not significant (slightly over USD 100,000).

Table 5: The Total Economic Revenue and Revenue Index of Nd Recovery based on Ext I and II Models

HDEHP-HCl (Ext I) System			**EHEHPA-HCl (Ext II) System**		
Particulars	**REEs**		**Particulars**	**REE**	
	Nd	**Dy**		**Nd**	**Dy**
Price (USD/kg)	70	281	**Price (USD/kg)**	70	281
Annual Revenue (USD)	533,484	142,734	**Annual Revenue (USD)**	533,484	142,734
Revenue Index	8,508	7,911	**Revenue Index**	10,418	21,804

However, adopting Ext I or Ext II in extracting Nd has tremendously improved the revenue rate of Dy. In the case of Ext II, the magnitude of increment in terms of revenue index from P350 is almost 7 times higher. In compared to P350, Ext II merely applies 7 separation stages as opposed to 10 stages (but with lower purity grade) in P350.

5. Conclusion

From this research it was found out that the extraction of neodymium from e-waste was an economically feasible process using the P350 extraction system. We were able to find out all the extraction parameters and the number of stages in extraction and scrubbing for each system. The annual expected revenue, expected annual production and revenue index were determined for all the cases and was compared in order to choose the most feasible system. Implementing such a system can lead to economic benefits and decreasing the amount of e-waste.

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