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ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF A PORTABLE E-WASTE RECYCLING AND RARE EARTH ELEMENTS RECOVERY PROCESS

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ABSTRACT

Over 40 million tons of electronic devices (e.g., computers, laptops, notebooks, and cell phones) became obsolete in 2020, and this estimate is expected to grow exponentially, mainly due to the decreasing lifespan of electronics. Most of the electronics replaced end up in municipal landfills. Electronic waste (e-waste) has raised concerns because many components in these products are not biodegradable and are toxic. Some of the toxic materials and chemicals include rare earth elements (REEs), which are currently experiencing supply constraints. This study focuses on generated e-wastes from households due to the high amount of these wastes. Technologies for e-waste mining must be tailored to household needs rather than large-scale industrial processes. The use of portable e-waste recovery systems may produce win-win outcomes where industry, households, and regulatory bodies could benefit, and this will incentivize e-waste mining for all stakeholders. This study investigates the sustainability benefits of employing a portable e-waste recycling and REEs recovery, using techno-economic and life cycle assessment methods. The results indicate that the proposed approach in this study mitigates environmental impacts when maleic acid is used as one of the key ingredients in recovering and separating REEs and other metals. It is concluded that when adopted globally, this technology can significantly address the e-waste challenge while improving the availability of REEs for high-tech applications.

Keywords: Rare Earth Element, Bio-Ore, Electronic Waste, Aeroponics, Hyperaccumulators, Sustainability, Life Cycle Assessment, Techno-Economic Analysis.

NOMENCLATURE

Parameters

i	Discount rate
$PM_{concentration}$	Precious metal concentration
$PM_{marketPrice}$	Precious metal market price
$REE_{concentration}$	Rare earth element concentration
$REEmarketPrice$	Rare earth element market price
R_t	Net cash inflow-outflows in a single period t
T_{cost}	Total cost
t	Time
$T_{revenue}$	Total revenue

Decision Variables

CAPEX	Capital expenditure
NPV	Net present value
OPEX	Operational expenditure
PP	Payback period
TP	Total profit

1. INTRODUCTION

A major challenge with consumer electronics is how they are discarded. The situation is worsened by the rapid turnover of consumer electronics due to their short useful life, less than three years [1]. Most of the electronics replaced end up in municipal landfills. Electronic waste has raised concerns because many components in these products are not biodegradable [1]. It comprises many components with valuable materials, some containing toxic substances that can harm human health and the environment [1]. Some of the toxic materials include rare earth elements (REEs) [2].

REEs are currently facing global shortages, and the need for a steady and unhindered supply of REEs from diverse sources is essential to satisfy technological needs in the coming decades [3]. For instance, the recycling rate of light REEs is low, and substitutes in most cases are either inferior or still undiscovered [4]. Conversely, the reliance on REE mining from ore does not provide an environmentally sustainable option. Ore mining requires significant material and energy consumption while generating large amounts of air and water emissions and solid wastes [5].

Overcoming light REE mining challenges could be solved with efficient REE recovery techniques for end-of-life products [6]. Today large concentrations of REEs are available in one location: landfills [7]. According to the United Nations' Stop the E-waste Problem program, global electronic wastes estimates for 2017 weighed eight times the Great Pyramid of Giza [8]. Additionally, prior studies reported that deposits of platinum group metals, such as gold, in e-waste are on average similar in concentration to large ore deposits currently available from traditional mines [9]. In other words, thirty smartphones contain as much gold as one ton of mined rock from a traditional gold mine [9].

Today, global management of e-waste continues to show significant differences between developed and underdeveloped countries. REE recovery challenges have created a cross-boundary movement of e-wastes globally to countries with limited or non-existent production capabilities in advanced countries. However, due to the lack of knowledge, informal workers in developing countries specialize in only a small palate of materials (e.g., copper), leaving behind precious metals (e.g., gold, silver, and palladium) and other high-value REEs [10]. For example, e-waste recycling practices in developing countries include manually grinding e-wastes (e.g., circuit boards) into fine powders for export [10]. Some recyclers engage in open incineration of cables and plastic to liberate copper from e-waste. In cathode ray tubes, the copper coil is stripped off, and the glass is crushed manually with stones.

These practices are hazardous to human health, the environment and yield no results in recovering REEs. Lee et al. (2011) proposed an integrated approach for gold (Au) recovery, using cyanogenic-bacteria (*Chromobacterium violaceum* and *Pseudomonas fluorescens*) along with pretreatment for bio-oxidation of e-waste by *A. ferrooxidans*, which removes Cu explicitly and leaves Au residues behind [11]. Then, Au and Ag can be extracted, using other microbes, such as *Acidithiobacillus* sp, *Leptospirillum* sp, *Ferromicrobium* sp, and *Acidiphilium* sp that can be combined with phytomining techniques.

With continued interest in clean energy technologies coupled with projected growth in power and transportation across the globe, the need for new methods of REE production and recovery must increase proportionately [12]. Developing nations are overwhelmed with e-waste management due because

most technologies intended to address REE recovery challenges live in journal publications rather than in industry [13]. In 2009, the U.S. EPA reported approximately 25% of the total electronics collected (2.37 million tons) were recycled, with the remainder disposed of in landfills [12]. In European Union, only a third of the e-waste volumes targeted by the law were collected and properly handled, with the rest disposed of in landfills or shipped illegally outside OECD states [14]. In developed countries, large-scale industrial processes face a contamination problem due to mixed waste streams in landfills. These challenges (collections, contamination, and limited technology) are the motivation for conducting this study.

During the past 20 years, the use of electronic devices (e.g., sensors and smartphones) has grown significantly to improve communication speed, entertainment, and information access. Growing demand for electronic devices implies a growing demand for critical materials. Urban mining, a form of closed-loop supply chain management or circular economy, offers an attractive alternative to e-waste management while reducing reliance on raw material from virgin sources [15]. A circular economy (CE) approach instead of a linear economy diversifies critical material resources and supply chains [15]–[17]. REEs in urban mines can be classified into two main categories, which are light REEs and heavy REEs. Presently, the recycling rate of LREE's is low [4]. Table 1 presents REEs sources from waste streams [18].

TABLE 1: SOURCES OF REES IN E-WASTE

REEs		Sources/Applications
Light REEs		
Lanthanum	La	Glass, ceramics, phosphors, pigments
Cerium	Ce	Polishing powders, ceramics, glass, alloy, UV filters
Praseodymium	Pr	Ceramics, glasses, pigments
Neodymium	Nd	Magnets, catalysts, IR filters, pigments for glass, lasers
Samarium	Sm	Constant magnets, microwave filters, magnets
Europium	Eu	Phosphors
Gadolinium	Gd	Medical imaging, optical and magnetic detection, crystal scintillators
Heavy REEs		
Terbium	Tb	Phosphors
Dysprosium	Dy	Phosphors, ceramics
Holmium	Ho	Ceramics, lasers
Erbium	Er	Ceramics, dyes forglass, optical fibers, lasers,
Ytterbium	Yb	Metallurgy, chemical industry
Lutecium	Lu	Single-crystal scintillators
Scandium	Sc	High strength Al-Sc alloys, electron bean tubes
Yttrium	Y	Capacitors, phosphors, microwave filters, glasses, oxygen sensors, radars

REE resources from e-waste can be classified into six categories (Figure 1), which are as follows:

- Temperature exchange equipment (e.g., air conditioner and fridges)
- Screen and monitors
- Lamps (e.g., light bulbs and LEDs)

- Large equipment (e.g., washing machines, electric stoves, heating systems, and photovoltaic panels)
- Small equipment (e.g., vacuum cleaner, irons, microwaves, toasters, and radio)
- Communication and handheld equipment (e.g., notebooks, cell phones, and tablets)

The composition of e-waste can also be grouped as follows:

- Metals (e.g., aluminium, copper, or iron)
- Plastics (e.g., PET, HDPE, PVC, LDPE, PP, and PS)
- Chemicals (e.g., lithium-ion batteries, Chlorofluorocarbons, and polybutylene)
- Glass
- Other substances (e.g., REEs and metals)



FIGURE 1: INDUSTRY AND HOUSEHOLD E-WASTES

E-waste recycling has significant health risks and can be found in dust samples adjacent to recycling workshops, roads, food stores, and schoolyards. Particularly, recycling circuit boards may present substantial environmental impacts and human health risks due to the toxic chemicals and heavy metals contamination (e.g., Cd, Co, Cr, Cu, Ni, Pb, and Zn). Prior studies show that lead and Cu in road dust were 371 and 155 times higher than non-e-waste sites located 8 and 30 km away, respectively. For instance, circuit board recycling has serious health risks to workers and residents of Guiyu, China, especially children [19].

The feasibility and analysis of recovering valuable materials from end-of-life applications is not new. Saidani et al. (2021) used a multi-tool methodology to evaluate action levers to close the loop on critical materials [17]. After a combination of material flow analysis, fuzzy-cognitive mapping, and structural analysis was conducted for platinum in discarded catalytic converters, they concluded that a CE represents a promising strategy if manufacturers integrate CE concepts into their designs to improve the recovery of critical materials in the life cycle of engineered systems [17].

This study proposes portable e-waste recycling and REE recovery systems which provide a means for e-waste producers to economically benefit from their e-waste instead of ad-hoc recycling paradigms, which rely on the voluntary action of consumers to achieve recycling goals[14]. When e-waste becomes a tradable and profitable good, or when consumers have technology to recover and trade essential materials from their e-waste, then a win-win outcome is achieved where industry, households, and regulatory bodies all benefit. The conducted sustainability assessment herein explores the potential of this approach through techno-economic and environmental assessments.

2. MATERIAL AND METHODS

This study focuses on midstream techniques (Figure 2) in the e-waste management process. E-waste to value-added materials (e.g., REEs, minerals, bio-ore) can be achieved through three main segments: upstream (mining and concentration), midstream (extraction and recovery, and separation and refining), and downstream (alloying and fabrication).



FIGURE 2: E-WASTES TO VALUE ADDED MATERIALS SUPPLY CHAIN (DOTTED LINE SHOWS THE FOCUS OF THIS STUDY)

The midstream segment includes various approaches for extraction and recovery, as well as separation and refining. The proposed process applies the aeroponic method, which is a way of growing plants with a fine mist of a nutrient-rich, water-mix solution, and without using soil. NASA applied the aeroponic method at the Mir space station in zero gravity that can grow both vertically and horizontally, and the growth is even better than the same plants on earth [20]. The developed procedure in this study contains (a) dismantling and weighing, (b) sono-bioleaching, (c) filtration and removal of leachate, and (d) sono-separation and phytoaccumulation in a magnetic field (Figure 3).

The dismantling and weighing step includes the disassembly of end-of-life electronics to separate REE-bearing components, such as microprocessors, microchips, and copper from electric cords. The REE-bearing microprocessors are then weighed to establish pre-processing weight. The sono-bioleaching step leaches out and increases REE concentration from e-waste, using a high-frequency sound and a soup of naturally occurring bacteria.

In bioleaching, heterotrophic organisms consume organic carbon sources and then produce organic acids, which are used in metal leaching. The bacteria produce energy for their growth by transferring electrons to clumps of rust and other surrounding metal oxides in a process called dissimilatory metal reduction. These electric bacteria are found in mud virtually everywhere on

earth, such as soil and compost heaps. The organic acids produce the dissolution of solids and have chelating properties, which promote REE solubility. When a high-frequency sound is introduced, acid production by the bacteria is accelerated, thereby increasing the rate of REE dissolution. The filtration step removes the contaminants in the leachate solution, either extracting or leaving REEs in the solution. The goal of this step is to increase the purity of REEs by removing contamination. To achieve REE separation, an ultrasonic reactor will be tuned to different frequencies. Ions of selected REEs in solution are then hyperaccumulated in the biomass of fungi, microbes, or plants. After the hyperaccumulator is harvested, it is then dried to become bio-ore and reuse.

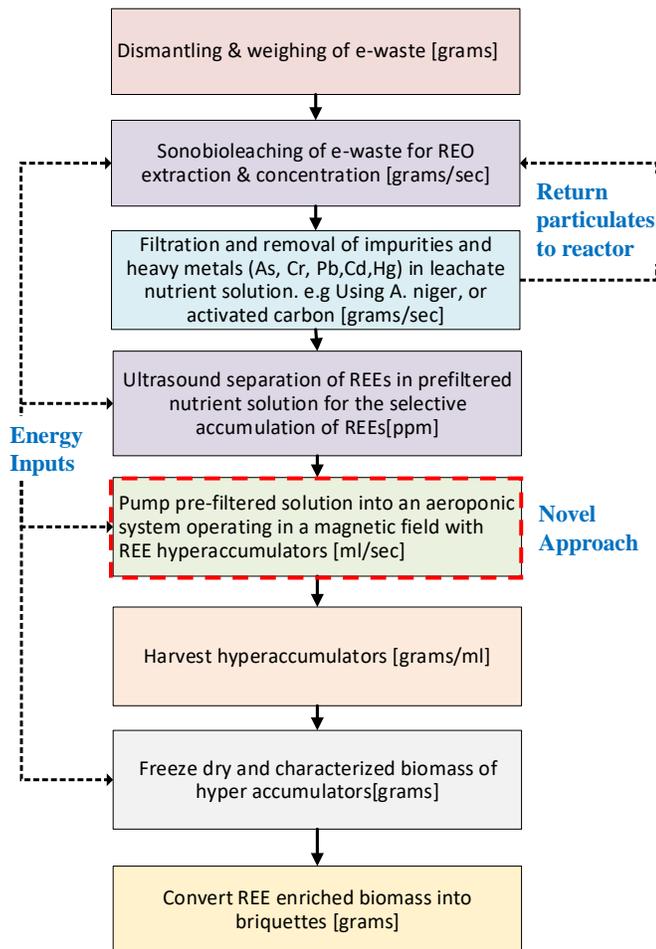


FIGURE 3: THE PROPOSED PROCEDURE FOR E-WASTE RECYCLING AND REE RECOVERY IN THIS STUDY

2.1 Environmental Impacts Assessment

Life cycle assessment (LCA) method is applied in this study for evaluating the environmental impacts of the e-waste-to-REE life cycle. The LCA study includes four main phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [21]–[23].

Goal and Scope Definition (Phase 1). This study aims to evaluate the economic and environmental impacts of a portable e-waste recycling process for household REEs and minerals recovery and purification. The scope of this study includes midstream processes and considers a gate-to-gate system boundary. Table 2 details the functional unit for inputs and outputs.

TABLE 2: INPUTS AND OUTPUTS CALCULATION AND FUNCTIONAL UNIT

Resources	Calculation (functional units)
Inputs	
E-waste	Mass (g/household)
Bacteria	Concentration (g/ml)
Plants	Mass flow rate (g/sec)
Water	Volume (ml)
Energy (ultrasonic and pump)	Energy consumption per day (kWh)
Transportation	Mass times distance (g × m)
Nutrients (NPK)	Volume (ml)
Outputs	
REEs	% purity of metal (g / (g + total g))

LCI (Phase 2). In order to accurately evaluate the proposed recycling and recovery process, data was obtained from prior published studies and available software/databases (e.g., OpenLCA and ecoinvent) [24]. In addition, several assumptions are made based on the available data for sustainability assessment. We assume each household in the US has the proposed process for REEs recovery. Then the produced REEs are transported to the distribution center within a certain mile radius.

LCIA (Phase 3). The LCIA is performed, using the OpenLCA version 2.0.4, CML-IA baseline impact assessment method. CML-IA is an LCA methodology developed by the Center of Environmental Science (CML) of Leiden University in The Netherlands. This method is an update of the CML 2 baseline 2000 and corresponds to publications by CML in August 2016 (version 4.7). The CML manual provides a list of impact assessment categories grouped into (a) obligatory impact categories (category indicators used in most LCA studies), (b) additional impact categories (operational indicators exist, but are not often included in LCA studies), and (c) other impact categories (no operational indicators available, therefore impossible to include quantitatively in LCA).

The impact categories of interest for the REE production system were as follows:

- Global warming: the Intergovernmental Panel developed the model on Climate Change (IPCC). Factors are expressed as global warming potential for time horizon 100 years (GWP100), in kg carbon dioxide equivalent per kg emission.
- Ozone layer depletion: the model is developed by the World Meteorological Organisation and defines the ozone depletion potential of different gases (kg CFC-11 eq) [25].

- Ecotoxicity: characterization factors, expressed as Human Toxicity Potentials, are calculated with USES-LCA, describing effects of toxic substances for an infinite time horizon.
- Eutrophication (fate not included): eutrophication potential and expressed in kg PO₄ equivalents per kg emission.

Interpretation (Phase 4). The major environmental impacts for REEs production from one household (1 kg e-waste) and the entire state of Idaho (469,645 kg e-waste) are calculated. The results are useful in grasping the key factors and variables. Additionally, the outcomes help determine future efforts in addressing sustainability challenges and national priorities.

Table 3 shows emissions to the environment from a household perspective compared to state-wide emissions when all households in Idaho participate in recycling e-waste and REE recovery, using the proposed approach in this study.

TABLE 3: SYSTEM INVENTORY FOR ONE HOUSEHOLD AND ENTIRE STATE OF IDAHO (469,645 HOUSEHOLDS)

Flow	Unit	Household	Idaho
Electronic waste	kg	1	469
Round Trip	t*km	0.001	469,645
Acetic acid	kg	0.453	212,749
Maleic acid	kg	0.453	212,749
Oxalic acid	kg	0.453	212,749
Fertiliser (N component)	kg	0.015	7,044
Fertiliser (P component)	kg	0.004	1,761
Energy from hydropower	MJ	4.95	2,324,743
Water	kg	0.004	469

Table 4 presents the environmental impacts of material inputs for REE production from a household perspective and state-wide perspective, using Table 3 data.

TABLE 4: ENVIRONMENTAL IMPACT CATEGORIES FOR ONE HOUSEHOLD

Impact category	Unit	Household	Idaho
Abiotic depletion	kg Sb eq	0	0
Abiotic depletion (fossil fuels)	MJ	0	0
Acidification	kg SO ₂ eq	0	0
Eutrophication	kg PO ₄ --- eq	0	0
Freshwater aquatic eco toxic	kg 1,4-DB eq	0	0
Global warming (GWP100a)	kg CO ₂ eq	0	0
Human toxicity	kg 1,4-DB eq	0	0
Marine aquatic ecotoxicity	kg 1,4-DB eq	0	0
Ozone layer depletion (ODP)	kg CFC-11 eq	0	0
Photochemical oxidation	kg C ₂ H ₄ eq	0.044	20,636
Terrestrial ecotoxicity	kg 1,4-DB eq	0	0

2.2 Economic Assessment

The economic analysis presented herein evaluates net present value (NPV), payback period (PP), and total profit (TP) for REEs production from e-wastes. Reasonable estimates were used where data was not available. The mathematical formulations of TP, PP, and NPV for the proposed problem are calculated, using Eqs. (1-5), where R_t is net cash inflow-

outflows during a single period t , which t is the number of periods, and i is the discount rate.

$$T_{\text{cost}} = \text{CAPEX} + \text{OPEX} \quad (1)$$

$$T_{\text{Revenue}} = \# \text{ harvest cycles} \times \% \text{ hyperaccumulating efficiency} \times [(\text{REE}_{\text{MarketPrice}} \times \% \text{ REE}_{\text{concentration}} \times \text{E-waste}_{\text{kg}}) + (\text{PM}_{\text{MarketPrice}} \times \% \text{ PM}_{\text{concentration}} \times \text{E-waste}_{\text{kg}})] \quad (2)$$

$$\text{TP} = T_{\text{Revenue}} - T_{\text{Cost}} \quad (3)$$

$$\text{NPV} = \sum \frac{R_t}{(1+i)^t} \quad (4)$$

$$\text{PP} = \text{CAPEX} / \text{Annual Cash Flow} \quad (5)$$

Table 5 shows the estimates used for the economic assessment based on the following assumptions:

- The proposed REE recovery process operates 24 hrs per day and able to process 4 kg of e-waste per cycle.
- There are 469,645 households in Idaho.
- The estimated plant hyperaccumulation efficiency is 50%.
- Percent concentration of REEs and noble metals (Au) in e-waste (magnets) is 31% and 0.0015%, respectively [26], [27].
- The minimum mass of e-waste processed per household is 4 kg (one cycle) per year.

TABLE 5: CAPITAL AND OPERATIONAL COSTS OF ONE CYCLE

Process	Capital Cost (\$/yr)	Operational Cost (\$/yr)
Dismantling	0	0
Pulverization	15	0
Pre-treatment	1,120	0
Phytomining	524	80
Harvesting/Drying	40	5.6
Total	1,6989	86

3. RESULTS AND DISCUSSION

The LCA results show that the proposed process (except for one impact category) has no environmental impacts (Figure 4). Based on the results, photochemical oxidation is a byproduct of the proposed process if acetic acid is used as a leaching agent. Photochemical oxidant formation (or photochemical smog) refers to a phenomenon under certain atmospheric conditions when pollutant-forming emissions are present. This observation is intensified when all 469,645 households in Idaho are put into the application. All other impact categories remain zero, meaning that even at large recovery rates across the State of Idaho, the process inputs have no environmental impacts.

The economic assessment shows an average gross annual profit of \$426 per household based on the recovery efficiency of hyperaccumulators and the design of the recovery system. The NPV for the proposed system during a four-year operating cycle at a discount rate of 7% is estimated a return of \$1,476 and the

PP in four years if the system is operated once a year to extract valuable metals from 4 kg of e-waste.

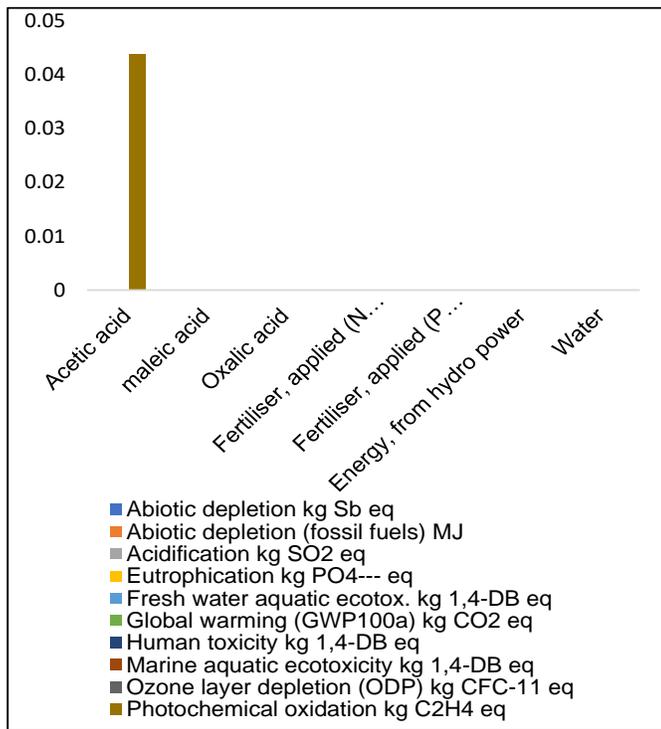


FIGURE 4: ENVIRONMENTAL IMPACTS OF THE PROPOSED PROCESS

The more e-waste recycled within the year, the quicker the payback period. This assumes stable market prices for non-REEs such as gold, cobalt, and REEs (neodymium and europium). When the State of Idaho incentivizes citizens to employ the REE recovery system in their homes at 30% discount, the state will

decrease the amount of minerals-rich e-waste being landfilled while benefiting economically. If 50% of Idaho households recycle 8 kg of e-waste per year, each household could earn a net profit of \$1,025/yr per recovery system after taxes (deduction of 7% State income taxes) annually. In 10-years, the State of Idaho would recoup all initial investment plus earn an income of \$63 million in the 10th year if households pay 7% of system profits for ten years (Table 6). Figure 5 presents the results of the economic assessment for one household over three years. In 3.5 years, each household would pay for the portable recovery technology.

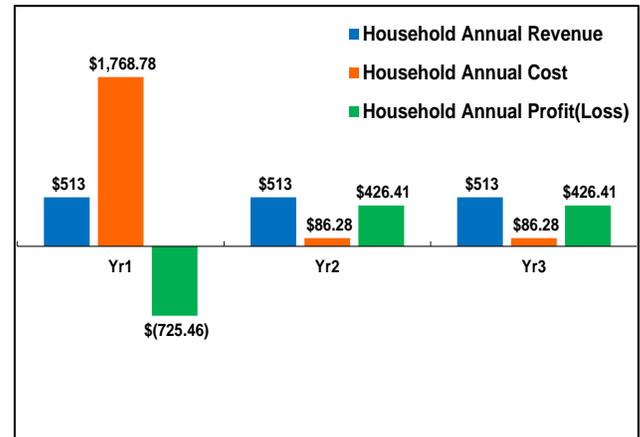


FIGURE 5: TOTAL PROFIT ASSESSMENT (ONE CYCLE)

Prior studies reported that maleic and oxalic acid could be used instead of acetic acid to achieve zero environmental impacts on the proposed process. Maleic acid can act as the key leaching solution in the process to mitigate the environmental impacts. Maleic acid is usually confused with malic acid, although they are two different acids [28], [29]. Maleic acid and malic acid are organic compounds and dicarboxylic acids that can be used in

TABLE 6: ECONOMIC ASSESSMET FOR THE PROPOSED E-WASTE RECYCLING AND REES RECOVERY

Years	Y1	Y2	Y3
Number of e-waste (magnets and PCBs) recycling and REE recovery	4	4	4
*Available mass of neodymium (Nd) in e-waste pile (kg)	0.087	0.087	0.087
*Available mass of gold (Au) in e-waste pile (kg)	0.304	0.304	0.304
*Available mass of other value metals in e-waste pile (kg)	3.352	3.352	3.352
% Concentration of gold in PCBs	0.0015%	0.0015%	0.0015%
% Concentration of Nd in magnets	31%	31%	31%
% Concentration of other value metals in e-waste	26%	26%	26%
Total mass of e-waste per recovery cycle (kg)	~4	~4	~4
Estimated plant extraction efficiency (%)	50%	50%	50%
Nd market price (\$/kg)	150	150	150
Gold market price (\$/kg)	55,241	55,241	55,241
Combined market price of other metals (\$/kg)	36,073	36,073	36,073
Total revenue (\$)	513	513	513
Process capital cost per recovery cycle (\$)	1,698.95	0	0
Process operational cost per recovery cycle (\$)	86.28	86.28	86.28
Total annual cost (\$)	1,785.23	86.28	86.28
Profit/loss without 30% state-wide discount (\$)	-1,272.54	426.41	426.41

* Estimates are based on the operational longevity of REE-bearing household electronics and the potential availability of these components during one recovery cycle.

leaching e-waste. One of the differences is malic acid has a chemical formula of $C_4H_6O_5$, while maleic acid has a formula $HO_2CCH=CHCO_2H$. The formula structure suggests that malic acid is a saturated dicarboxylic acid, whereas maleic acid is an unsaturated dicarboxylic acid. These organic acids are easily degradable and have been employed as leaching agents in previous studies to minimize the acid-leaching process's environmental impacts [30]. Also, they reported that organic acids (e.g., maleic acid, acetoacetic acid, and glycolic acid.) could achieve high leaching efficiencies of valuable metals from spent lithium-ion batteries [30]. Therefore, a closed-loop process of recovery-resynthesize can be achieved when organic acids are employed as the leaching agents. Their results show that maleic acid has higher leaching efficacy and availability in comparison to other organic acids. This would reduce the REE recovery cost and minimize the emission of hazardous substances to the environment.

Plant-based separation techniques using wheat and other hyperaccumulators (e.g., *Berkheya Coddii*, *Alyssum Bertolonii*, *Haumaniastrum Robertii*, and *Brassica Juncea*) have been found to exhibit metal absorption properties [31]. *Berkheya Coddii* has several advantages over other hyperaccumulators due to their ease of growth from seed. It is a perennial plant, tolerant of cooling climate conditions, prolific reproduction of seeds, resistance to insects and soil pathogens, can be harvested and regrown, and high accumulation of metals. Additionally, earlier studies show that adding some compounds (e.g., EDTA and citric acid) to soils increases metal solubility while keeping soil parameters (e.g., pH, osmotic potential, and nutrient availability) within the growth range of the plant. These compounds are also relatively inexpensive [32]. Recent studies reported that phytomining (i.e., removing toxic metals from the soil, using fast-growing plants) for nickel is a viable approach. For instance, *Alyssum Bertolonii* and *Berkheya Coddii* have the potential to adsorb nickel from polluted soils. Phytomining can be cost-effective, depending on the metal value, particularly noble metals could be effectively phytomined at low concentrations in plants [32].

Msuya et al. (2000) induced hyperaccumulation in five root crops, which are: carrot, red beet, onion, and two cultivars of radish with chelates NH_4SCN and $(NH_4)_2S_2O_3$ in a substrate, containing 3.8 mg/kg gold [33]. After nine weeks, NH_4SCN and $(NH_4)_2S_2O_3$ were applied to the substrate at the rate of 1.0 g/kg and 2.0 g/kg, respectively. Carrot roots yielded the maximum gold concentration among those five root crops, making it the most cost-effective crop for phytomining. Carrots yielded 0.78 kg/ha with NH_4SCN and 1.45 kg/ha with $(NH_4)_2S_2O_3$. Msuya et al. (2000) estimated a total allowance of \$6,950 per hectare for agronomic, incineration, and chemical costs [33]. After excluding the total allowance, the maximum yield was a minimum of \$840 when NH_4SCN was applied, and a minimum of \$7,550 when $(NH_4)_2S_2O_3$ was used [33].

Earlier studies investigated mushroom hyperaccumulators (e.g., *Macrolepiota procera*) for adsorbing REEs [34]. The results showed that Cerium (Ce) was the most abundant REE in edible caps of the mushroom. Furthermore, Falandysz et al. (2016) concluded that the mean concentration of 14 REEs (i.e., Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm, and Yb) in the caps of mushroom was 0.5 mg/kg of dry biomass and 0.75 mg/kg dry biomass in the whole fruiting bodies of the mushrooms [34]. The use of mushrooms would find useful applications in recovering REEs from bauxite tailings at bauxite mining sites [35], [36]. Similarly, Haselwandter K et al. (2010) concluded that *Suillus granulatus*, *Suillus luteus*, and *Pleurotus ostreatus* also show levels of REE concentration in their fruit bodies [37]. After the REEs have been concentrated in plant and fungi biomass, further REE separation is achieved through incineration, hydrometallurgical, or electrochemical processes [38].

4. CONCLUSION AND FUTURE DIRECTION

There are numerous studies about phytoaccumulation, phytomining, and phytoextraction. However, these methods have been applied in lab-scale research, and neither concepts have been adopted commercially because of the difficulties in raising crops for mining purposes. Several challenges, such as weather unpredictability, pest control issues, availability of large acres of land for commercial phytomining, the need for fertilizers, low concentration of minerals in the soil, and fluctuating market value of minerals are among the factors prohibiting the adoption and commercialization of phytomining technology for REEs recovery from e-waste.

Integrating various techniques for domestic e-waste recycling and REEs recovery can be a promising approach for addressing REE supply challenges while minimizing the environmental impacts of e-waste in landfills. REEs recovery requires different processes, depending on REEs concentration, the economics of recovery processes, and the targeted metals. The proposed portable e-waste recycling and REEs recovery process in this study could help overcome global e-waste collection challenges, leading to a significant reduction of e-waste in municipal landfills. This study performed techno-economic analysis (i.e., NPV, PP, and TP) and environmental impacts assessment, using LCA method. The results show that the applied organic acids (e.g., maleic acid, glycolic acid, and acetoacetic acid) for e-waste recycling are naturally existing in plants and animals, and are environmentally friendly agents.

The potential paths for future research include (1) exploration of reaction mechanisms based on parameters in the acid-leaching process, (2) investigation of thermodynamic, kinetic properties, and the availability of organic acids, and (3) exploration of the leaching condition, acid concentration, solid-liquid ratio, temperature, and reaction time of organic acids.

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