CHAPTER 6

COST-BENEFIT ANALYSIS OF PROPOSED RECYCLING ROUTE

6. COST-BENEFIT ANALYSIS OF PROPOSED RECYCLING ROUTE

6.1 Cost-Benefit Analysis (CBA)- General working framework

Cost-benefit analysis was done for economic assessment of recovery of metals from waste tantalum capacitors to determine the economic attractiveness of the developed recovery method. CBA was performed following a three-step methodology which are; i) identification of pathway through which raw material (WTC) will pass during its recovery process ii) process simulation, and iii) economic analysis.

During the entire recovery process, the WTC passes through three main stages. Detailed flowsheet showing various stages/processes through which material passes during the recycling is shown in *Figure 6.1*. First is the collection stage, where WTCs are purchased for further processing. Then in the 2nd stage i.e., the treatment stage, the waste is treated for recovery of valuable metals. In the 3rd stage, the recovered products/by-products are either sold to the market (finished product) or to other secondary producer (by-products) for its further processing. Once the stages are identified, the next step is process simulation, where a detailed flowsheet with mass-balance was developed. The elemental balance through various stages of treatment was assessed depending on the chemistry of products obtained after each stage of treatment. Finally, the economic analysis was carried out based on the cost of developing the overall recycling process involving the cost of initial raw material (WTC) purchase, labor, lease, building and machinery, construction, material and energy, maintenance, management, and the revenues generated from the products/by-products obtained after recycling. The indirect cost and benefits have been excluded from the present framework of study.

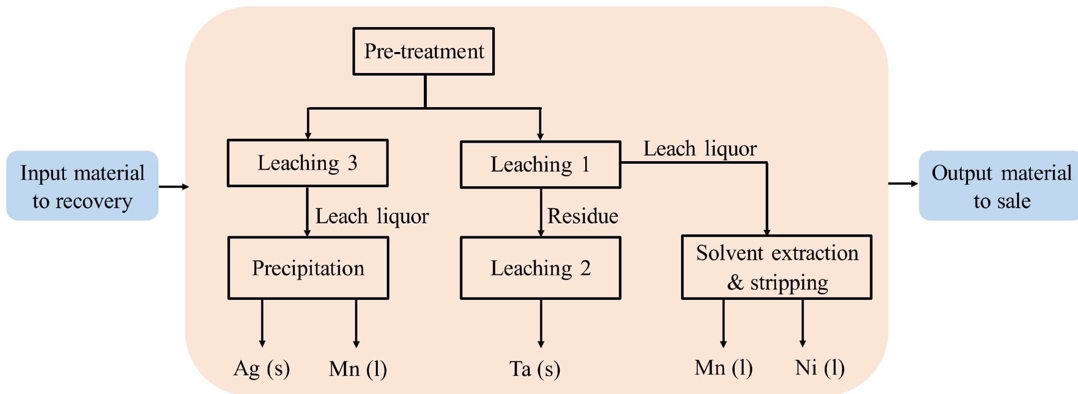

Figure 6.1 Major stages in recovery process of WTCs

6.2 Cost estimation

Using the process mapped in *Figure 6.1*, the cost and benefit for treatment of WTCs is calculated. The first step while conducting cost analysis is to define the cost elements. The cost elements for the present study are fixed capital cost (lease, building, equipment, construction, and equipment maintenance cost) and variable operating cost (material, energy, labor, and management cost). For the initial economic assessment of recovery of metals from WTCs, collection cost and transportation cost are not included. After defining the cost elements, individual cost is determined. The economic assumptions made to conduct this analysis are listed in *Table 6.1*.

The various components of capital cost considered in this study are motivated from the real life scenarios in Indian industries and the numbers are obtained from the experts of this area. To determine the operating cost, various unit process shown in *Figure 6.1* was reviewed in details. The quantity of individual input material needed to process 220 kg of WTC per shift was determined by conducting all the experiments in laboratory. The input material used in the present study include nitric acid (HNO_3), hydrochloric acid (HCl), carrier for solvent extraction (CYANEX272), kerosene, ammonia, sodium chloride (NaCl) powder, distilled water (DI), and electricity. Whereas, the output are metals (tantalum, manganese, nickel, and silver) in solid and liquid form. The various chemical reagents consumed during the recycling treatment can be recycled and re-used after each cycle using the standard practice available on the literature (McKinley and Ghahreman, 2018). However, for simplified cost estimation, recycling of chemicals was not considered in the present analysis. Therefore, all the reagent consumption data shown in this chapter is based on the single-cycle use (except solvent extraction carrier). For solvent extraction stage, it was assumed that the carrier used in extraction is regenerated after stripping and can be used up to 10 cycles (2% loss in each cycle) without losing extraction efficiency and then after 10 cycles it is recycled with 95% recycling efficiency.

Table 6.1 Economic assumption to carry out cost benefit analysis

Parameters	Assumption
Analysis year	2022
Capacity	220 kg of waste capacitors / shift
Shift/day	3
Working days/week	6 days
Depreciation method	Straight-line depreciation (10% for equipment and 5% for building)
Number of labor	5/shift
Unit labor cost	600/day/shift
Land	450 sq. meter
Construction cost	8000 INR/sq. meter
Selling price for recycled metal (by-product)	75% of market price of that metal

The prices of input material were obtained from industrial grade chemical supplier and multiplied with total material needed for the experiments to determine the total material cost. The energy cost for processing 220 kg of WTCs was calculated based on the quantity of electricity required multiplied by cost of electricity for industrial use. After knowing the material and energy cost, the total number of labor required was assumed and multiplied with average wage rate per shift for India to calculate the total labor cost. Management cost was taken as 30% of labor cost.

After determining total cost, revenue generated was calculated from the total quantity of metal produced after recycling. Selling price for main end-product was calculated directly by multiplying quantity of metal produced to market cost of that metal. However, revenue from by-product (metal which was not in finished form and needs further processing) was calculated by multiplying quantity of metal produced to 75% of market cost of that metal.

6.3 Cost benefit analysis results

6.3.1 Process results

The elemental balance flowsheet for the developed process for recycling of metals from tantalum capacitors is shown in *Figure 6.2*. The numbers displayed on the flowsheet represent the outcomes of the AAS, ICP-MS, and SEM-EDS analyses, as described in the previous chapters. The initial composition of the raw tantalum capacitor is 40% tantalum, 4% manganese, 1.2% silver, 1% nickel, 0.35% iron, and the rest organic material, which contains silica. After hammering and handpicking, the metal-rich fraction was separated with 89% tantalum, 8.7% manganese, 2.2% nickel, 1.23% iron, and 0.12% iron. However, majority of silver from the tantalum capacitor predominantly entered into the non-metallic fraction, making up 2.26 % silver. Both of the fractions, metallic and non-metallic, undergoes a number of processes, as can be seen in *Figure 6.2*, to recover the target metals. The composition of the products obtained after each successive stage of treatment is given in the flowsheet. The final recovered products after undergoing all the treatments are tantalum (99.99% purity), manganese (99.6% purity), nickel (95.5% purity), and silver (99.99% purity).

The metallurgical balance flowsheet for this process is shown in *Figure 6.3*. In the metallurgical balance flowsheet, metals which were in very low concentration and were not significant for the process were not reported quantitatively. Quantitative analysis was done based on the obtained results (shown in *Figure 6.2*) in laboratory experiments. The calculation was performed for treating 220 kg of material in one batch. This 220 kg of WTCs containing 110 kg organic matter with SiO_2, 90 kg tantalum, 8.8 kg manganese, 2.2 kg nickel, 2.64 kg silver, and 0.77 kg iron was divided into two separate fractions i.e., metallic-rich concentrate and organic matter rich concentrate, each weighing 100 kg and 115 kg, respectively, with 5 kg (approximately 2% of initial raw material) material being lost as dust. At the end of the process, 88.98 kg of tantalum (s), 7.75 kg of manganese (l), 2.199 kg of nickel (l), and 2.3 kg of silver (s) are produced as the final output metals, with tantalum being the finished product and the other metals being by-products that need additional processing.

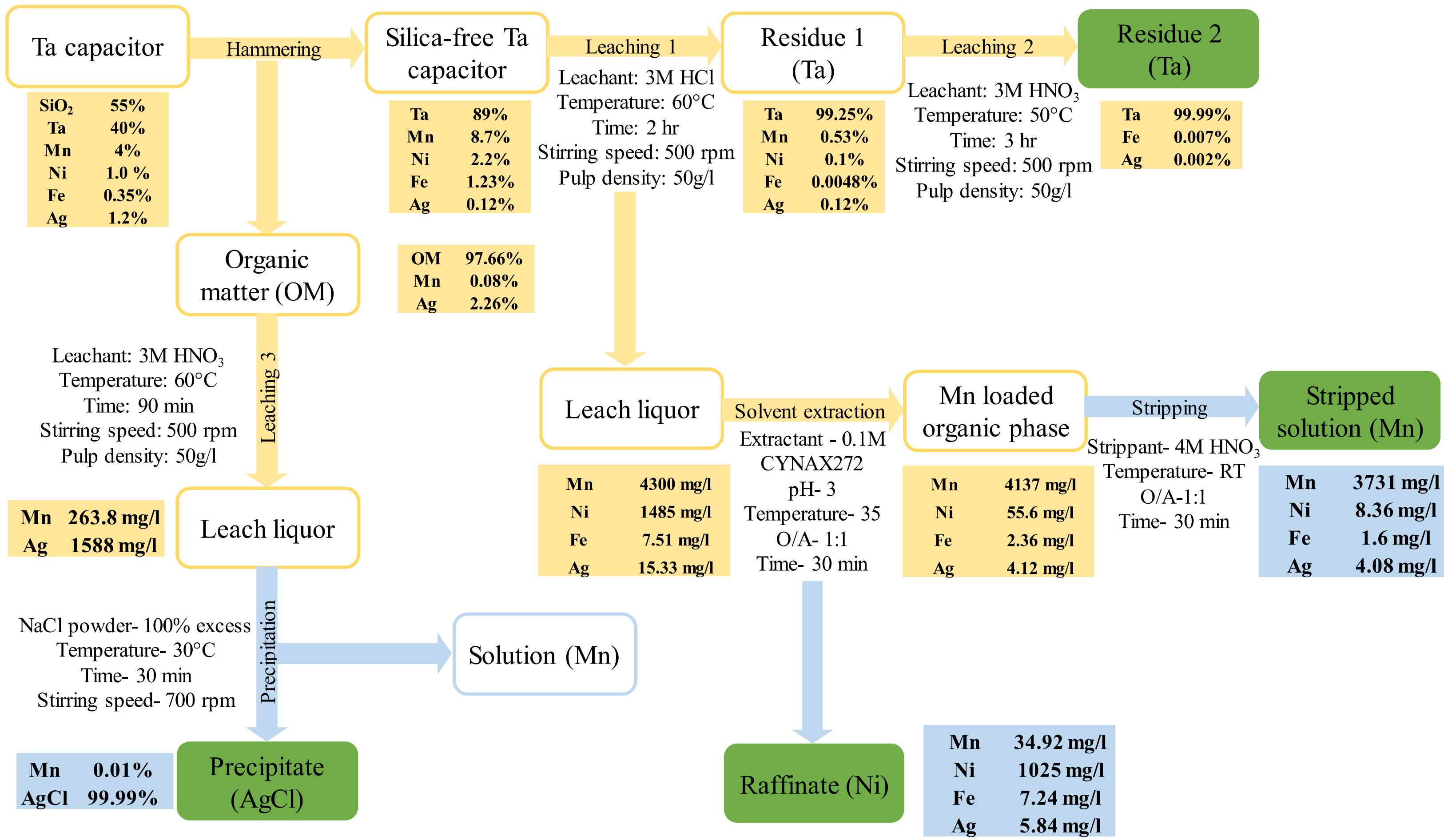

Figure 6.2 Elemental balance of proposed recycling route during various stages of treatment

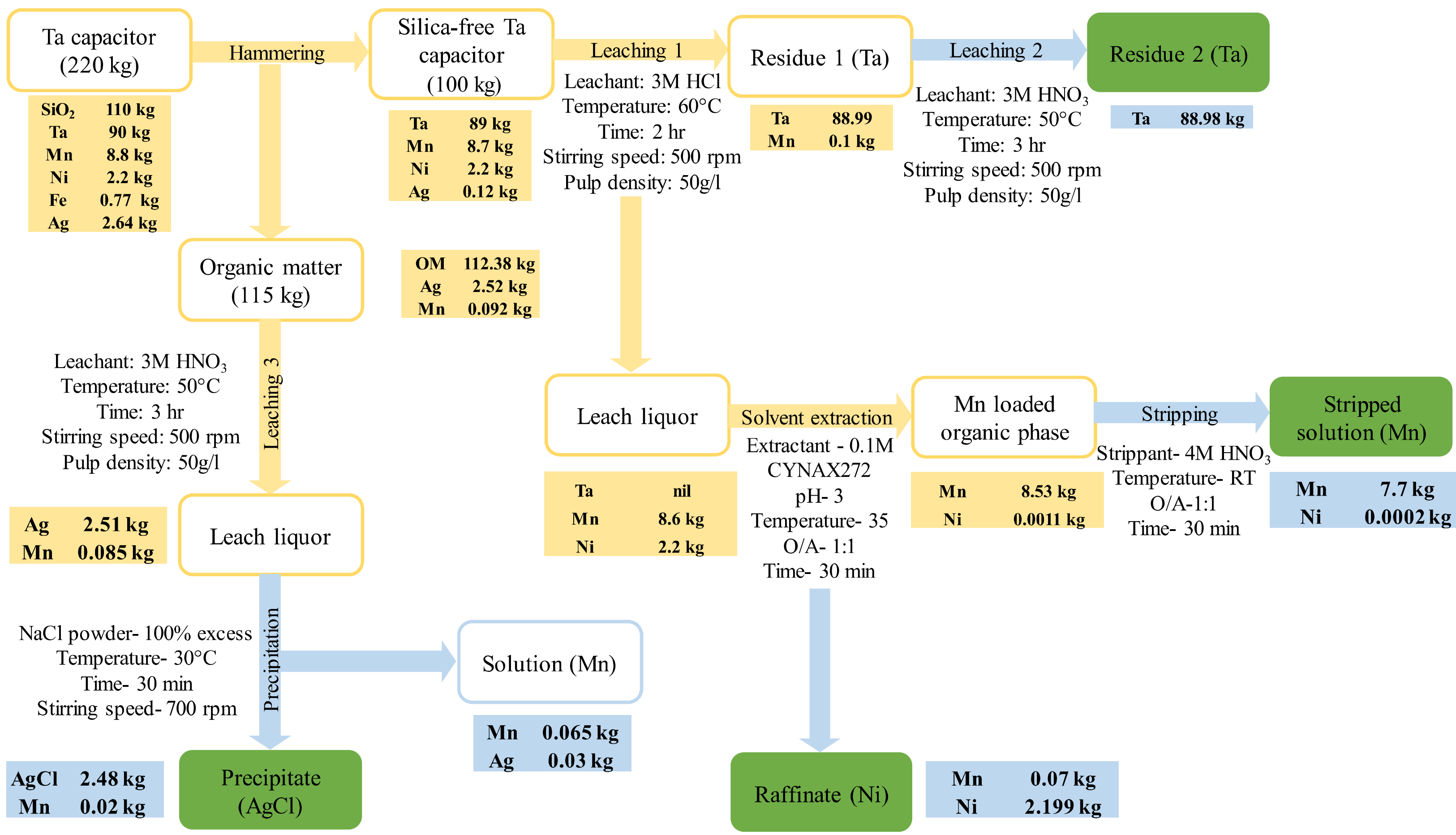

Figure 6.3 Metallurgical balance of proposed recycling route during various stages of treatment for treating 220 kg of WTCs per cycle

6.3.2 Economic analysis results

Recycling cost for treating 17160 kg of waste capacitors per month (220 kg/shift) is calculated from the quantity of input material (raw material and energy) needed which is presented in *Table 6.2.*. The cost of total recycling treatment is 1,32,75,481 INR. Cost contribution from individual treatment stage is presented in *Figure 6.4*. The figure shows that solvent extraction and stripping contribute the most to the total recycling cost, with a share of around 54% and 34%, respectively, whereas chemical precipitation only contributes 0.06%. The leach liquor obtained after the 1st stage leaching was diluted four times before being treated with solvent extraction and stripping. This larger volume of solution and the more expensive reagent (CYANEX272) are the reasons for the higher cost of solvent extraction and stripping.

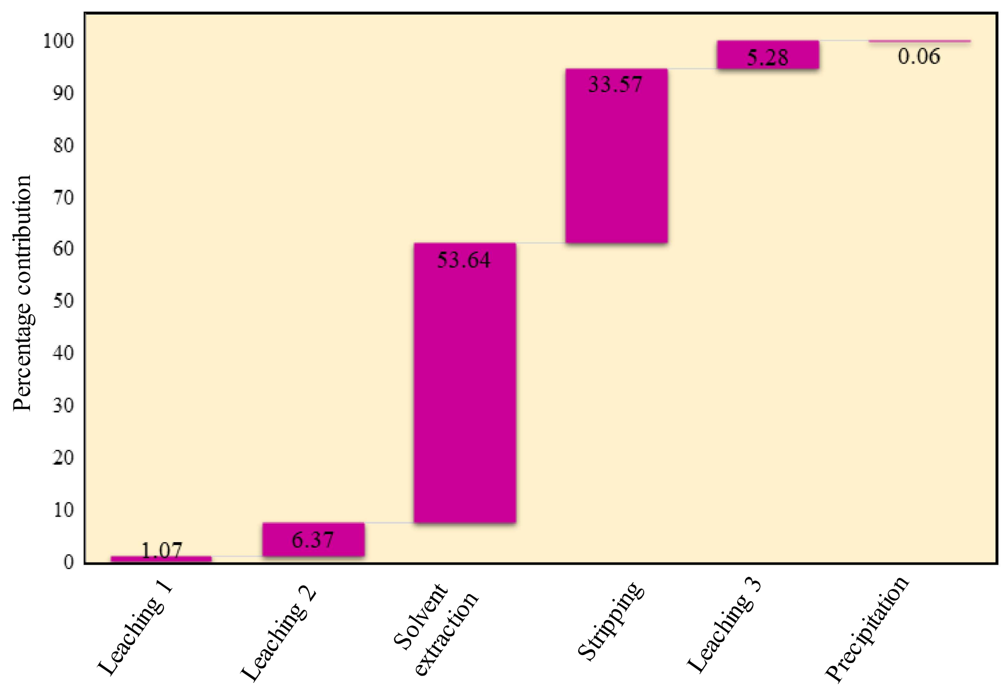

Figure 6.4 Contribution of the individual process area to total recycling cost

Table 6.2 Quantity of input material needed and their price for treatment of 220 kg of WTC/shift for a month (All the prices are in INR)

Process	Input		Quantity	Price/unit	Total price/shift	Total price/month
Leaching 1	Material (Ltr)	HCl	492.8	3.5	1,725	1,34,534
	Energy (KWH)		8.0	12	96	7,488
Leaching 2	Material (Ltr)	HNO_3	382.2	28	10,703	8,34,812
	Energy (KWH)		12.0	12	144	11,232
Solvent Extraction	Material (Ltr)	CYANEX272	618.4	10000	61,840	48,23,520
		Ammonia	400.0	62	24,800	19,34,400
		Kerosene	7381.6	62.7	4,628	3,61,004
	Energy (KWH)		2.0	12	24	1,872
Stripping	Material (Ltr)	HNO_3	2040.0	28	57,120	44,55,360
	Energy (KWH)		2.0	12	24	1,872
Leaching 3	Material (Ltr)	HNO_3	318.5	28	8,918	6,95,604
	Energy (KWH)		6.0	12	72	5,616
Precipitation	Material (kg)	NaCl powder	2.7	30	80	6,294
	Energy (KWH)		2.0	12	24	1,872
Total treatment cost					**1,70,198**	***1,32,75,481***

Besides this recycling cost, other costs calculated is given in *Table 6.3*. Overall cost for processing of 17160 kg of WTC/month is calculated to be 18,56,29,013 INR. In the cost structure, the largest component is the raw material i.e., waste tantalum capacitor cost which itself is responsible for 92% of total cost which might be due to its high critical metal (tantalum) content. Following this, other major cost is treatment or recycling cost with 7% of total cost. Finally, there are capital cost, management cost, DI cost, and maintenance cost with a total share of less than 1%.

Table 6.3 Total cost and benefits of treatment of 220 kg of WTC/shift for a month

Cost & Benefits	INR
Cost/month	
Lease cost	1,670
Building cost @5% depreciation	12,500
Construction cost	3,00,000
Plant and machinery @10% depreciation	25,000
Equipment maintenance cost@10% of machinery	2,500
Labour cost@600/labour	2,34,000
Waste Ta capacitor cost	17,16,00,000
Distilled water (DI) cost	1,07,665
Recycling cost/month	1,32,75,482
Management cost	70,200
Total cost	**18,56,29,013**
Revenue/month	
Sales revenue from tantalum	35,53,50,528
Sales revenue from manganese	1,13,928
Sales revenue from nickel	2,36,700
Sales revenue from silver	84,58,164
Total sales revenue	**36,41,59,321**
Total profit before tax / month	**17,85,30,308**

To determine the revenue, four recycled metals (tantalum, manganese, silver, and nickel) recovered after the treatment that can be sold directly are taken into consideration. Among those metals, tantalum is in finished form as powder and can be sold to consumer market directly. Whereas, silver, manganese and nickel are in intermediate form and will need further treatment and therefore can be sold to further processing units. *Table 6.4* shows that tantalum accounts for the highest sales revenue among the recycled metals due to its higher cost and alone responsible for 97.58% of total revenue. After tantalum, silver is the second major contributor in revenue with 2.32% share, even after being 2.48 kg of total output weight, which is due to its high economic value. Manganese and nickel together stands at less than 0.1% of total revenue which is not surprising from the abundant availability of these metals causing the marker price to be low. According to these estimates, a recycling facility will produce a total profit of 17,85,30,308 INR in a month when operated on an industrial scale, bringing the overall profit margin to 50%.

Table 6.4 Quantity of output material and its price for treatment of 220 kg of WTC/shift for a month (All the prices are in INR)

Output	Quantity (kg)	Price/kg	Total revenue/shift	Total revenue/month	% share to total revenue
Tantalum	88.98	51,200	45,55,776	35,53,50,528	97.58
Manganese	7.79	250	1,460	1,13,928	0.03
Nickel	2.20	1,840	3,034	2,36,700	0.06
Silver	2.48	58,300	1,08,438	84,58,164	2.32
Total revenue			**46,68,709.0**	**36,41,59,321**	

6.4 Sensitivity analysis results

Some of the key parameters used in this study are often associated with uncertainties. Therefore, it becomes crucial to conduct a sensitivity analysis to evaluate the impact of variations in these parameters to the total profit percentage. The aim of this study was to contribute to an improved insight in the factors that determine the economic feasibility of treatment of WTCs on industrial scale. This analysis was performed by identifying the most dominant parameters influencing the profitability of running the proposed recycling facility. The parameters included for this study are WTC cost, recycling cost, tantalum, and silver market price. The parameters were varied by ±40%, ±30%, ±20%, and ±10%. Only one parameter was varied at a time while the remaining was kept constant. The results of sensitivity analysis are shown in *Figure 6.5 (a-d)*.

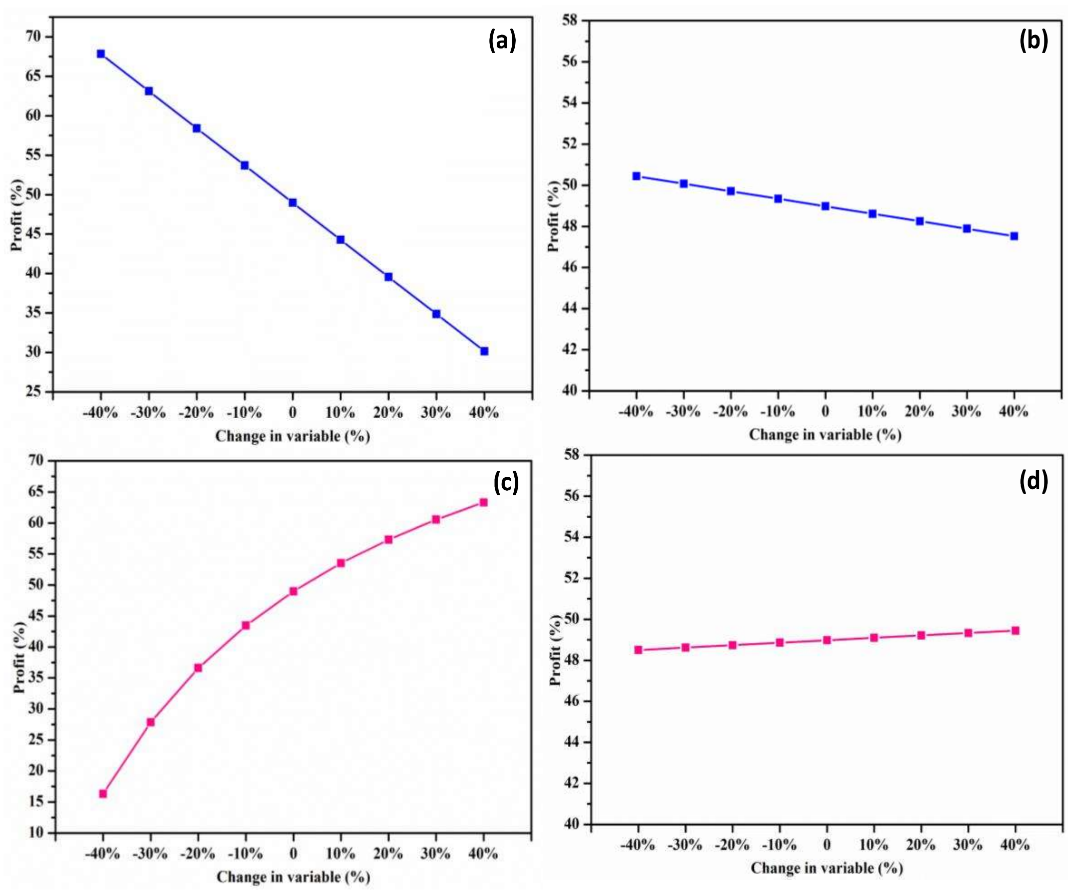

Figure 6.5 Effect of variation on (a) WTC cost, (b) Recycling cost, (c) Tantalum, and (d) Silver market price on percentage profit

It can be seen from the *Figure 6.5* that WTC cost and market price of tantalum are the most sensitive parameters to the profitability. For example, with a minimum 10% increase in the WTC cost, the percentage profit drops to 44% from a base value of 49% (*Figure 6.5*a). A further change in WTC cost on either side results in an inverse change in profit with a similar slope. Similarly, the variation in market price of tantalum significantly affects the profitability of the recycling facility. A 10% increase in tantalum prices increases the profit to 53.5% from a base value of 49%, whereas; an increase in price by 40% will lead to increase in profit to as high as 63% (*Figure 6.5*c). On the other side, a decrease in tantalum price remarkably decreases the profitability. It is of interest to note that even with a drop in tantalum price by 40%, the recycling facility will still have a profit of 16%. The impact of other factors, such as recycling cost and the price of silver, is minimal. Despite a 40% rise in recycling cost, the overall profit only falls by 1.5% (*Figure 6.5*b). In a similar vein, a 40% increase in the price of silver results in a 1.5% increase in overall profit (*Figure 6.5*d).

6.5 Scenario analysis results

In reality, the variables that are considered for the sensitivity analysis typically vary simultaneously. So different scenarios in which the most significant parameters from the sensitivity analysis i.e., WTC cost and price of tantalum were varied concurrently to determine its impact on the overall profit gained from the recycling. The scenarios considered in this analysis are most optimistic, optimistic, base case, pessimistic, and most pessimistic. The details of each scenario are given in *Table 6.5*. The consequences of each of this scenario on total cost, revenue, and profit is illustrated in *Figure 6.6*. It can be seen that in the most optimistic scenario i.e., 40% reduction in WTC cost and 40% rise in tantalum price, the total profit achievable is 38,93,10,516 INR (77% profit). By moving from most optimistic to most pessimistic scenario, the total cost increases with a decrease in total revenue and overall profit. However, the rate of increase in total cost is approximately half to the rate decrease in the total revenue. In the case of most pessimistic scenario i.e., 40% rise in WTC cost and 40% reduction in tantalum price, the total cost of running this recycling facility surpasses the total revenue of recycled metal and therefore making the overall profit negative. Based on this analysis it can be suggested that, the most feasible scenarios for successfully running this recycling facility at industrial scale is from the most optimistic to pessimistic for which the total profit percentage ranges from 77% to 25%.

Table 6.5 Details of different scenarios considered for scenario analysis

Scenarios	WTC cost	Ta price	Profit (%)
Most optimistic	-40%	+40%	76.86
Optimistic	-20%	+20%	65.19
Base case	0%	0%	48.98
Pessimistic	+20%	-20%	24.89
Most pessimistic	+40%	-40%	-14.60

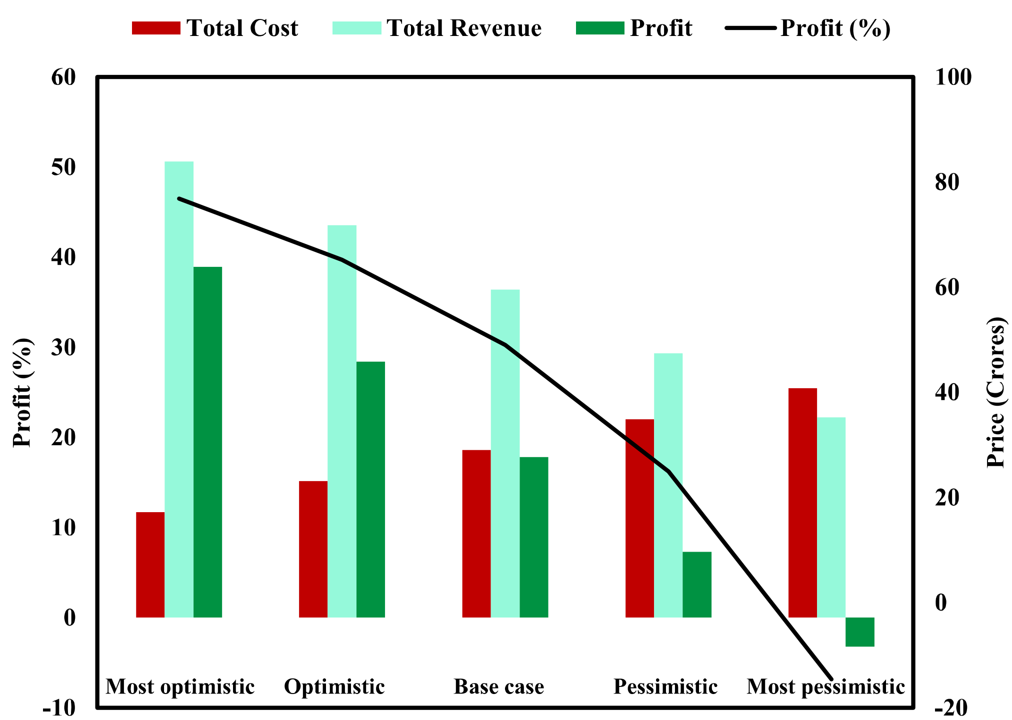

Figure 6.6 Effect of different scenarios on total cost, revenue, profit, and percentage profit for running the proposed recycling facility for a month

6.6 Discussion

The proposed method in this study is a simpler yet efficient method for treatment of WTC ending up in e-waste pile-ups. The existing methods on recovery of tantalum from WTC are very complex, requiring several steps to produce the metals of desired purity, and are mainly limited to recovery of single metal (Mineta and Okabe, 2005; Niu et al., 2017d; Xia et al., 2021). However, the method proposed in this work requires minimal steps to produce the metals (specially tantalum) of desired purity. Also this method allows sequential recovery of all four economically and strategically significant metals with high recovery efficiency and minimal loss in intermediate steps. The obtained recovery efficiency of tantalum, silver, manganese, and nickel is 98.87%, 93.93%, 88.23%, and 99.95%, respectively. The high recovery yield of all the metals enables maximum resource efficiency with the minimal amount of waste. The non-metallic fraction, which is the only residue of the entire treatment process, can also be transferred to the facility working with non-metallic fraction recycling for its effective use to reach the ultimate goal of "*zero waste*".

In terms of cost and benefit analysis, the suggested approach has a significant potential for profit, mostly because it contains a significant amount of pricey tantalum. Operating this recycling facility can generate about twice as much money as it would cost, to make approximately 49% profit. However, the sensitivity analysis reveals that the profitability of running this recycling facility is mostly sensitive to two factors i.e., WTC purchase cost and market price of tantalum. On the one hand, with a contribution of almost 98% to overall sales, tantalum is the primary factor determining the total revenue. On the other hand, in the cost structure, the WTC cost makes up the majority of the total cost i.e., 92%. If the cost of this raw material is reduced while the price of tantalum is raised, the profit margin might be boosted even further, and vice versa. The recycling cost is next significant factor in cost, after WTC purchase cost, with 7% share. The process of solvent extraction and stripping, which is dedicated to manganese and nickel recovery, is contributing the most to this overall recycling cost. Therefore, the total recycling cost can be minimized further by choosing a cheaper carrier for selective separation of manganese or by maximizing the recovery efficiency of metal in a single cycle. Moreover, if the recirculation of organic carrier can be further promoted, this will also help in reducing the overall consumption of carrier and thereby minimize the recycling cost and will eventually help in reducing the overall cost (to some extent) of running this recycling facility.

The scenario analysis proves that the suggested technology has the ability to be employed on an industrial scale from the most optimistic to the pessimistic scenario, with profit percentages ranging from 77% to 25%. This can either be established as a standalone unit that solely handles used tantalum capacitors, or can be integrated with an existing e-waste recycling facility where the components that are rejected from the printed circuit boards can be transferred for additional processing. The current economic analysis is suggested for a small-scale recycling operation that processes 220 kg of WTC every shift. Depending on the availability of labor and raw materials, the plant's capacity may be expanded.

6.7 Conclusions

In this chapter a detailed elemental and metallurgical balance was established to quantify the input and output of metals throughout the recycling treatment. Moreover, a cost benefit study was conducted to assess the economic feasibility of proposed recycling route at an industrial scale. The major outcomes of this chapter is given below:

- The mass balance of the proposed recycling route showed that from the input of 90 kg Ta, 8.8 kg Mn, 2.2 kg Ni, and 2.64 kg Ag, the output of 88.98 kg Ta, 7.7 kg Mn, 2.199 kg Ni, and 2.48 kg Ag is obtained.

- The economic analysis demonstrated that the suggested recycling route is quite profitable, with a 50% profit margin.
- The sensitivity analysis revealed that the largest impact on profitability is due to the purchase cost of WTC and sales price of tantalum. Other factors do not significantly affect the total cost and sales structure, thus their impact on profitability as a whole was modest. A drop in the WTC purchase price or a rise in the tantalum sales price can further boost the overall profit.
- The outcomes of the scenario analysis also demonstrated that the method is appropriate for use on an industrial scale, from the most optimistic to the pessimistic scenario, with profits ranging from 77% to 25%.