CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1 Electronic waste (e-waste)

Discarded electrical and electronic equipment (EEE), which has completed their average lifetime and is no longer useful for consumers is termed as e-waste (Işıldar et al., 2018). Rapid technological advancement coupled with increased consumer demand led to the increased production volume of advanced EEE. This increased production volume together with the shortened lifespan of electronic gadgets, inadequate awareness among users, and lack of international consensus on waste electrical and electronic equipment (WEEE) management is responsible for exceptional growth of e-waste generation (Agrawal et al., 2022a; Friege, 2012; Rao et al., 2021a). E-waste is one of the world's fastest single waste stream with an annual growth rate of 3-5%, three times faster than other municipal waste stream (Huang et al., 2009; Ilankoon et al., 2018). 57.4 Mt of e-waste was generated globally in 2021 which is estimated to reach 74 Mt by the end of 2070. Out of this huge generated e-waste, the portion which was formally collected and recycled was just 17.4% while the remaining 82.6% ended up as e-waste pile-ups (Forti et al., 2020b). Continent-wise e-waste generation data and their respective recycling rate (RR) are given in *Figure 1.1*. It can be seen that Asia is the largest e-waste producer with roughly 50 wt% contribution followed by Americas, Europe, Africa, and Oceania. Out of these continents, Europe accounts for the largest share towards recycling of e-waste with RR of 42.5% and Africa contributes smallest share with RR of only 0.9%. The large RR in Europe is the result of their various policies such as extended producer's responsibility (EPR), setting of collection points and pick-up centres, take-back scheme, etc. are strictly functioning in different parts of the continent, regulated by the WEEE Directive (2012/19/EU) (Forti et al., 2020b; Union, 2020).

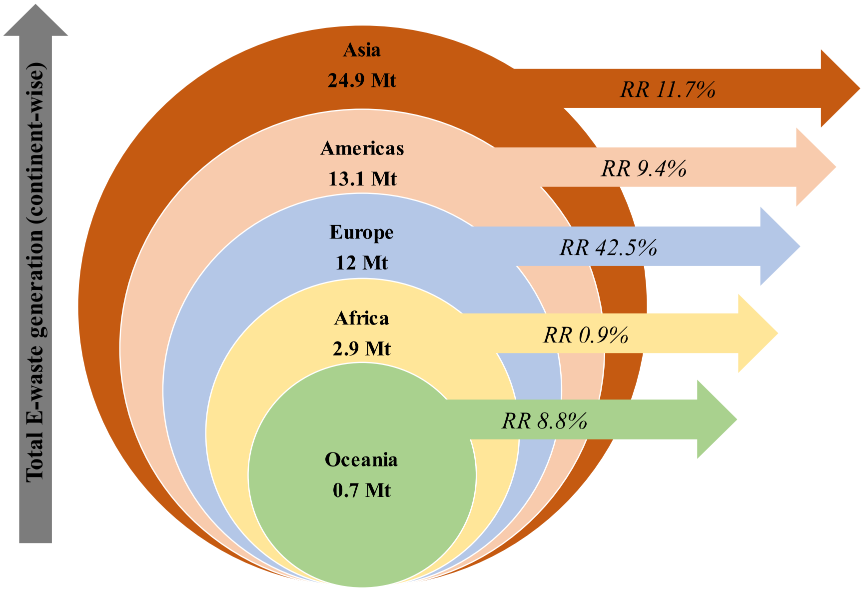

Figure 1.1 Total e-waste generation continent-wise and their corresponding recycling rate (RR) in 2019 (Forti et al., 2020b)

1.2 Printed circuit board assembly (PCBA)

Printed circuit board assemblies are the core of any electronic gadget (Hadi et al., 2013). These PCBAs are 3-6 wt% (Lu et al., 2022) of the total e-waste amount and even higher in some electronic products like colour TV (7.04 wt%), PC control unit (18.76 wt%), and mobile phone (21.30 wt%) (Hadi et al., 2013; Wang and Xu, 2014). PCBAs are the complex structure which is composed of 60 different elements (Bloodworth, 2014) including toxic, precious, critical, and base metals (Cui and Forssberg, 2003). With the developments in electronic industry, the average manufacturing rate of PCBAs has also grown annually to 8.7% globally and 10.8% in Asia (Ilankoon et al., 2018). The metal content in these PCBAs are 10-100 times higher than naturally occurring minerals, which makes it a highly valuable resource for secondary production of metals. PCBAs are composed of bare printed circuit board (PCB) and welded electronic components (ECs) which are briefly described in the following sub-sections.

1.2.1 Printed circuit boards (PCBs)

PCBs are composed of metals, ceramics and plastics with relative proportion of 40%, 30%, and 30%, respectively (Kaya, 2016). PCB is a basal plate that is used to support and connect different ECs to one another via conductive track. It has laminated sandwiched type structure where conductive copper layer are laminated onto nonconductive substrate made of glass-fibre reinforced epoxy resin (Işıldar et al., 2018; Wikipedia, 2023). ECs are either mounted on to conductive pads as surface mounted device (SMD) or is plated through-hole. This bare PCB is approximately 23% of total board weight (PCBA) (Duan et al., 2011). Weight of bare PCB to total device varies with the type of device for example; the total weight share of bare board is 2%, 11% (Fan et al., 2013), and 22% (Chancerel et al., 2009) for large electronic device, laptops, and mobile phones respectively.

1.2.2 Electronic components (ECs)

A major fraction (>70%), by weight, of PCBA are made of electronic components. ECs are classified into "precious" and "non-precious" type based on their precious metal content (Jianbo Wang et al., 2017). Major ECs used in manufacturing of PCBA are shown in *Figure 1.2*. Integrated circuits (ICs), central processing units (CPU), diode, transistor, random access memory (RAMs), tantalum capacitor, and multilayer ceramic capacitor are categorized under precious components as they contain highly valuable metals like gold, silver, tantalum, palladium, gallium, barium. Whereas, aluminium electrolytic capacitors (AECs), inductors, resistors and some other auxiliary parts are categorized as non-precious components due to its lower value (Wu et al., 2022). Among these ECs, AECs are the most populated components in any electronic device with total share of 20 wt%. Besides that, tantalum capacitors (TCs) are another widely distributed components due to their superior capacitance per unit volume as compare to other types of capacitors and is more valuable due to its critical metal content. Together, these capacitor makes 24% of total weight of

PCBA. Besides this, ICs, CPUs, and RAMs also has high intrinsic value due to their presence of precious metal like gold and silver. On a rough approximation, the content of metal in these waste electronic components (WECs) is 50% while remaining being the non-metals i.e., plastics, ceramics, glass, and electrolyte.

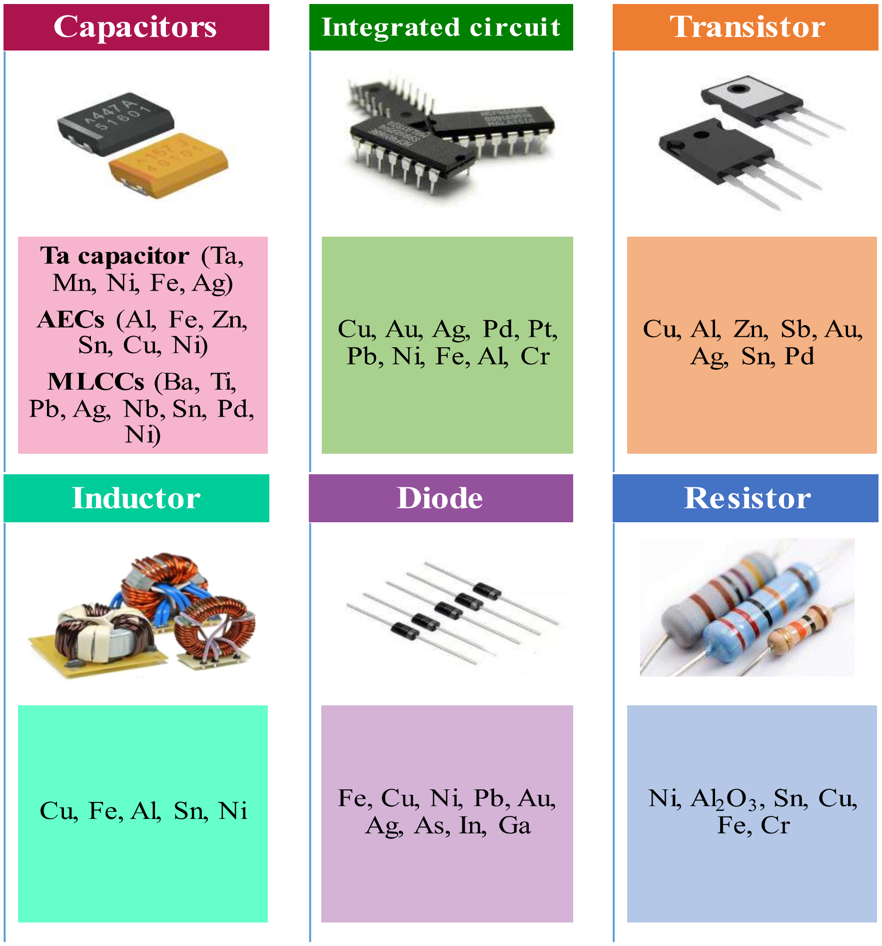

Figure 1.2 Major electronic components used in PCBA and metals present in it (AECs- aluminium electrolytic capacitors, MLCCs- multi-layer ceramic capacitors)

1.3 Tantalum in electronics

Tantalum is used in electronics in the form of tantalum capacitors, tantalum nitride (TaN) resistors, integrated circuits, and Surface acoustic wave (SAW) filters. Out of these, tantalum capacitor is one of the most valuable components mounted on the PCB. Nearly

40% of the total tantalum is consumed by the capacitor segment which are then employed in biomedical implants, portable EEE, and vehicles. Due to excellent stability and resistance to moisture, TaN thin-film resistors are used in automotive, industrial, and aerospace applications (Ibidunni, 1993; Nieberl et al., 2023). Besides this, tantalum is often employed as a diffusion barrier in integrated circuits and in data storage technologies. SAW filters, composed of chemicals like lithium tantalate ($LiTaO_3$), are used in digital audio transmission, 4G communication, and automotive navigation (Ku, 2018; Nieberl et al., 2023).

1.3.1 Tantalum capacitor

The capacitor market serves as the leading end-user of tantalum due to its' high volumetric efficiency that has enabled exceptional miniaturization of electronic gadgets—a prime demand of today's growing high-tech society (Mancheri et al., 2018; Schulz et al., 2017). The capacitors are used in many high-end applications such as smartphones, desktop computers, laptops, servers, hard disk drive (HDD), implantable cardioverter-defibrillator (ICDs), etc. (Agrawal et al., 2022b; TIC, 2018). Based on the data published by (Ueberschaar et al., 2017),potential of tantalum capacitor associated with different electronic gadgets is shown in *Figure 1.3*. According to this data, largest potential of tantalum is found in desktop PCs and notebook, whereas; lowest potential is found in smartphones. However, the content of tantalum into different electronic gadget and its distribution pattern among them is a function of manufacturing year. For instance, mobile phones made before 2008 consumed more tantalum than those made after that year (Christian et al., 2014). In spite of that, the high tantalum content in the WEEE, make it an attractive secondary resource for recovery of tantalum.

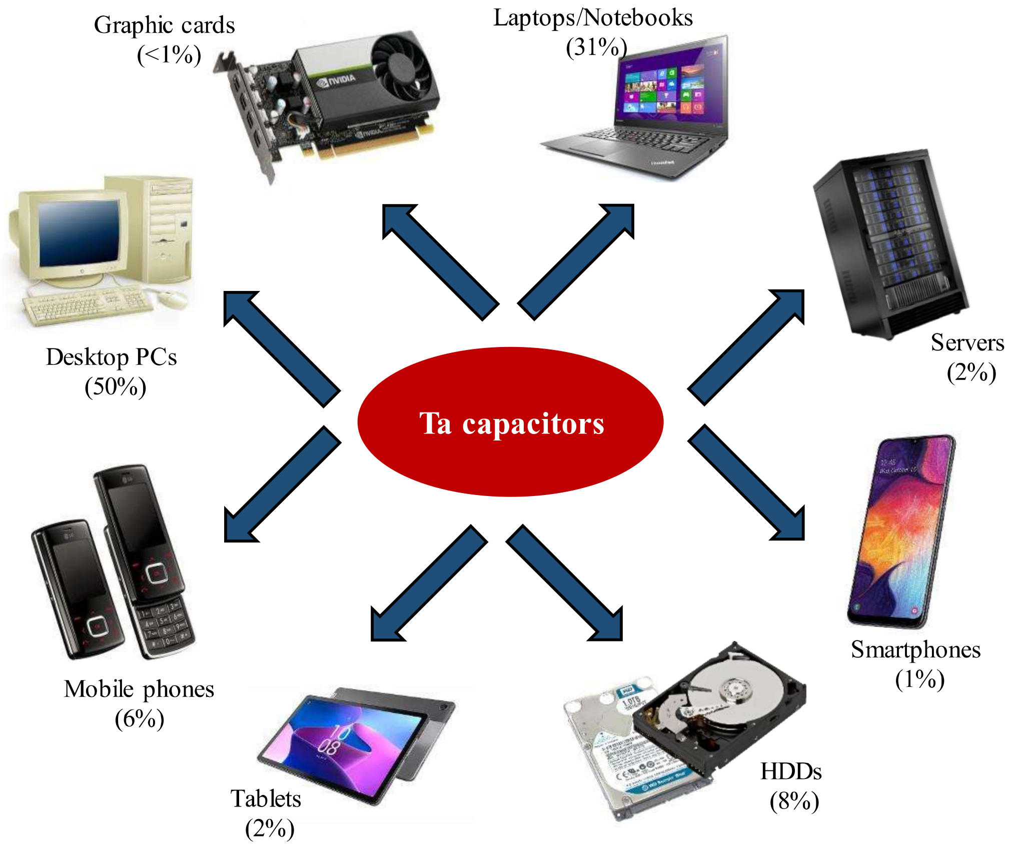

Figure 1.3 Potential of tantalum capacitor in different electronic devices

Tantalum capacitor offers several advantages over other capacitors (AECs, MLCCs, etc.) such as high reliability, higher frequency, highest capacitance in a small volume, absence of acoustic noise on the application of electrical signal, and stable capacitance with DC bias over a wide range of temperature (TIC, 2017). The most commonly used capacitors other than tantalum capacitors are aluminum electrolytic capacitor, multilayer ceramic capacitors (MLCCs), polymer solid aluminum capacitor, and in some instances, niobium capacitor. The high volumetric efficiency of tantalum capacitor in smaller size is the prime reason which replaces the need of a chunky aluminum capacitor or several MLCCs.

Even though the share of tantalum capacitors in the overall capacitor market is small, yet a large proportion of tantalum being utilized in the manufacturing of these capacitors accounts for the high sensitivity of the price of tantalum with respect to demand (Vulcan, 2009). Other than that, scarcity of tantalum leads to its unstable supply and cyclic shortage, as seen in the year 1997, 2000, and 2008 (Nassar, 2017). The price hike as a result of supply strain of tantalum in given year led to substitution of tantalum capacitors with MLCCs and AECs (Mancheri et al., 2018; Nakatani, 2010; Zednicek et al., 2002). These alternative technologies often associated with several limitations such as DC leakage instability of niobium capacitor, logarithmic capacitance degradation with time (i.e., aging phenomena) in the ceramic capacitor (Brunette, 2019), and lower capacitance. All these factors makes these capacitors less efficient compare to tantalum capacitor (Freeman et al., 2012).

1.4 Opportunities of metals recovery from waste tantalum capacitors (WTCs)

Out of several other essential metals present in WPCBs of waste electrical and electronic equipment (WEEE), tantalum is one of the most valuable rare metal because its superior characteristics. Properties such as hardness, high melting point, very strong yet ductile, “ultimate” corrosion (Fontana, 1987) and wear resistance, high capacitance/volume, bio-compatibility, high-temperature strength, etc. have made its use indispensable in a wide array of highly specialized applications in many industries such as automobile, aerospace, defence, electronics, optics, chemical processing, and medical *Figure 1.4*. Out of these, electronic segment is the largest consumer of tantalum due to their superior capacitance (Agrawal et al., 2021; Schulz et al., 2017).

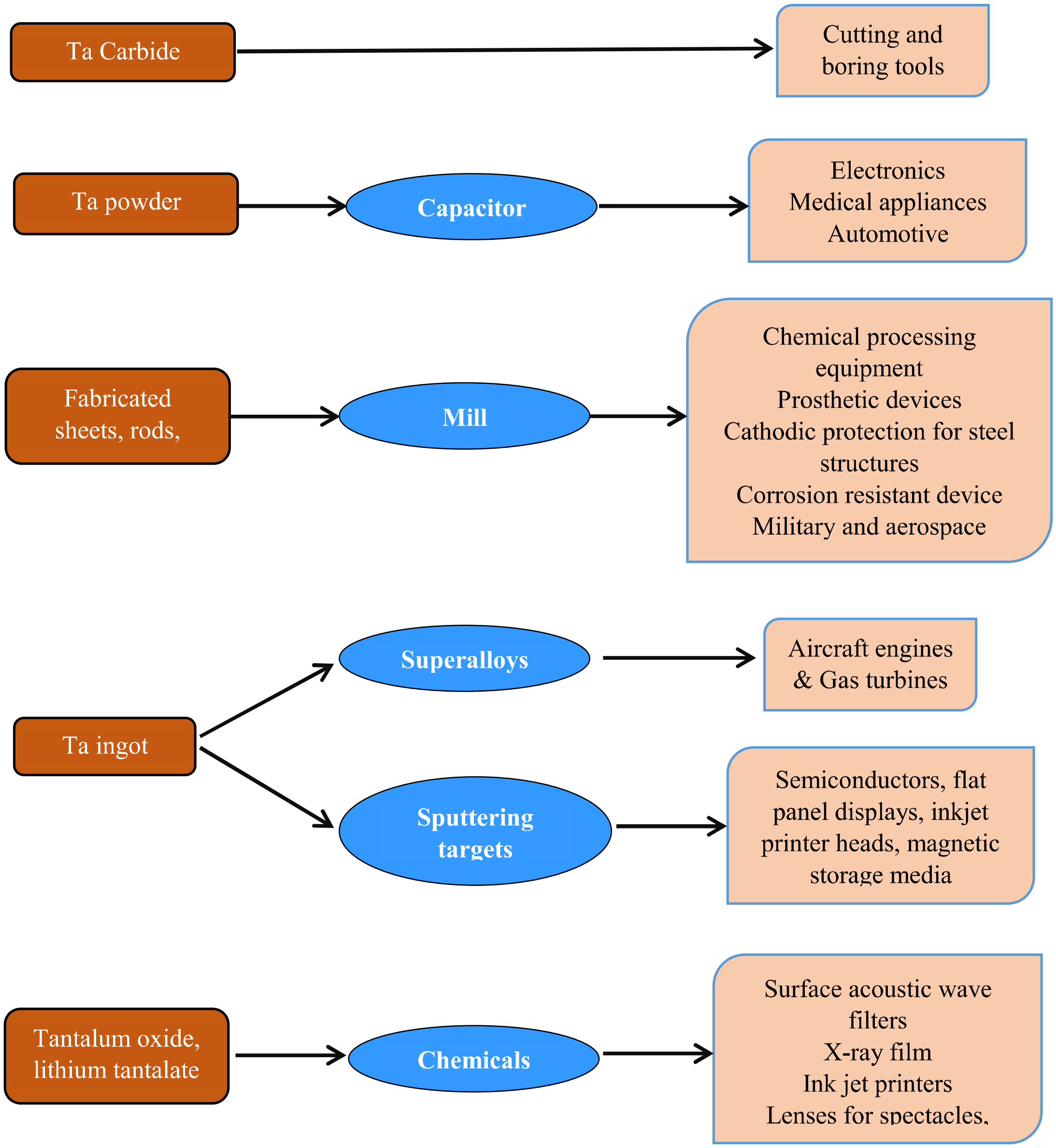

Figure 1.4 Major end-use applications of Tantalum (Mancheri et al., 2018; Nassar, 2017; Soto-viruet et al., 2013)

In our modern economy, tantalum has evolved as a "technology-critical element" owing to the rapid digitalization of the world (Filella, 2017). A material's criticality is appraised based on the outcome of the supply shortage of the material and the associated supply risks (Zimmermann and Gößling-reisemann, 2013). In general, a material is termed as 'critical' when there is a high risk of a supply shortage as well as a massive impact of material's supply on the economy of the world in comparison to most of the other raw materials

(Zimmermann and Gößling-reisemann, 2013). Since 2017, the supply risk for tantalum has increased. Moreover, tantalum's economic value is growing in capacitors, electro-optical systems, and gas turbine engines (TIC, 2021). Contrary to major metals, including Cu, Fe, and Ni, the yearly primary production of tantalum is limited (1850 tons in 2019) (U.S. Geological Survey, 2020). It can be seen from the *Figure 1.5*, tantalum mine production has consistently lagged behind demand over the years. Furthermore, tantalum has been classified under the category of "conflict mineral", together with Sn, W, and Au, since a major portion of its production is concentrated in the Democratic Republic of Congo (DRC) and other African regions where mining has financed rebel movements (Mancheri et al., 2018). Indeed, tantalum is an indispensable commodity for the society due to its numerous high-end applications. Therefore, a sustainable supply of tantalum is essential.

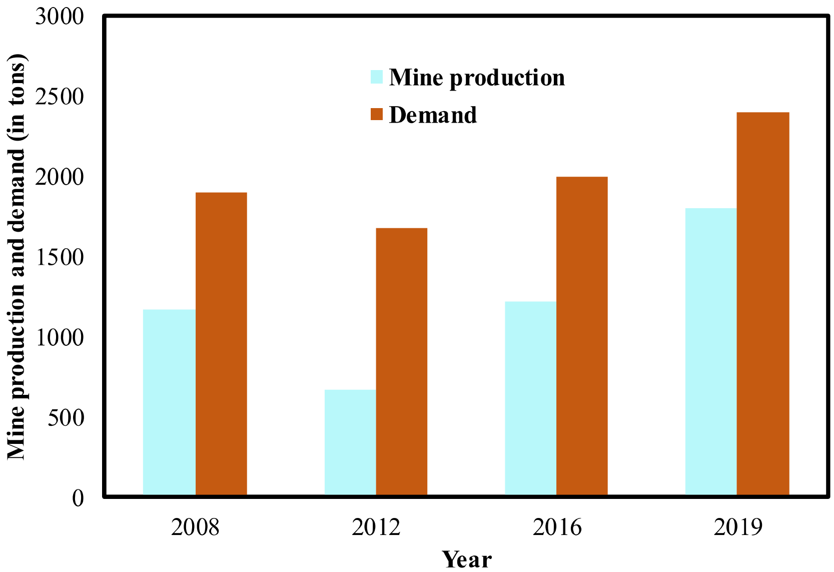

Figure 1.5 Statistical data representing demand/supply of tantalum year-wise (Roskill, 2019; Stratton, 2013a; TIC, 2018)

Tantalum does not appear in the free metallic form. Naturally occurring minerals of tantalum originate in the form of complex mineral oxide and hydroxide. Examples of such minerals include wodginite, tantalite, euxenite, columbite, microlite, etc., which consists of nearly 12-85% of tantalum in the form of tantalum pentaoxide (Ta_2O_5). Out of these, tantalite and columbite (together, called "coltan") are the most commonly used mineral for the extraction of tantalum. These minerals are a combination of tantalum and niobium oxides. In fact, niobium is always associated with tantalum due to their chemical similarities (Filella, 2017; Papp, 2011). The association of chemically similar niobium along with tantalum ore makes the primary extraction process very difficult and demands a tremendous amount of energy for its removal. This waste capacitor scrap contains a significant amount of tantalum (more than its primary resources) and is free of niobium. The higher content of tantalum in capacitor scrap, free of niobium, and its high economic value is making it an attractive alternative resources for the cleaner production of metal and sustainable resource and energy utilization perspective (Matsuoka et al., 2004; Mineta and Okabe, 2005; Niu et al., 2020).

Aside from tantalum, the capacitor contains a number of other valuable metals, including silver, manganese and nickel, that are strategically and economically significant. After tantalum, manganese is the most abundant metal in the capacitor. Manganese has been recently added to the list of critical metals by U.S. Geological Survey due to its economic value and a potential risk of supply disruption (Vieceli et al., 2021). Manganese has an indispensable use in steel production and battery manufacturing (Chan et al., 2021; Vieceli et al., 2021). In practice, manganese is the fourth most widely utilized element in tonnage behind iron, aluminum, and copper (Sinha and Purcell, 2019). Other than manganese, nickel is widely used in plating, catalyst, superalloys, aircraft and aerospace application due to its superior properties and its demand is further increasing. As a result of increasing demand, its prices are upsurge in the recent past (Coman et al., 2013; Odegbemi et al., 2021). Even though it is the 24th most abundant metal in the earth crust (Meshram et al., 2019), the high cost and rapid depletion of rich ores necessitates to look for secondary means of supply of the metal. Recycling capacitors can thus alleviate the aforementioned concerns while also entailing a sustainable supply of these strategic metals.

1.5 Literature review

1.5.1 Bibliographic mapping

A bibliometric mapping of the publications related to e-waste and tantalum capacitor recycling has been built to analyse the literature quantitatively. For this purpose, the Scopus database is selected for the literature review of the technical articles. The Scopus database is the largest abstract and reference source of peer-reviewed literature. In the Scopus database, various combination of words is searched by using 'AND', and their results are shown *Table 1.1*. The search included technical articles, articles in the press, books, book chapters, conference reviews, conference articles, editorials, notes, short surveys, review articles, etc. Co-occurrence analysis of the author keywords was performed to find the significant terms utilised in these documents. The keywords related to each article have been extracted from a comma-separated value (.csv) file from the Scopus database. The co-occurrence network map was created with the help of VOSviewer® developed by Nees Jan van Eck and Ludo Waltman at Leiden University's Centre for Science and Technology Studies (CWTS). The entire number of keywords was separated into clusters, which were shown on the map in different colours. The size of the circle indicates the frequency of the keyword occurrence, and the proximity of the circles indicates the co-occurrence of the keywords, i.e., the closer the two circles are, the higher the frequency of their co-occurrence (van Eck and Waltman, 2014).

The Scopus results showed that e-waste was a broad term that resulted in a large number of documents (5922). The term 'tantalum capacitor' was searched to keep our search limited to the scope of the study, and it returned 1997 documents. Because the search was further narrowed by utilizing the key phrase 'tantalum capacitor recycling' a small number (49) of documents were found. The bibliometric mapping is performed using documents found through a search for the term 'tantalum capacitor'. A total of 9699 keywords were found in 1997 documents. When the minimum occurrence bar was set to 20, the number of keywords was reduced to 170 and grouped into five clusters, as illustrated in *Figure 1.6*. To further investigate the frequency of occurrence of these terms in literature, the minimum occurrence bar was adjusted to 5, bringing the total number of keywords to 871 and grouping them into seven clusters, as shown in *Figure 1.7*. From both the figures it can be seen that, the terms recycling and tantalum recovery have limited occurrence in the literature, while the term tantalum capacitor recycling does not appear at all. As the co-occurrence bar was set to 5 (*Figure 1.7*), the relevant terms (recycling, tantalum recovery, etc.) appearance was increased with greater connection to tantalum capacitors. This bibliometric mapping reveals that research on tantalum recovery from capacitor scrap is scarce. Through the present research work, an effort has been made to bridge this gap in the literature.

Table 1.1 Number of research articles found in the Scopus database

Keyword searched (Title-abs-key)	Scopus results
E-waste	5922
E-waste recycling	3330
Tantalum capacitor	1997
Tantalum capacitor recycling	49
Tantalum capacitor and e-waste	12
Tantalum capacitor and e-waste recycling	10

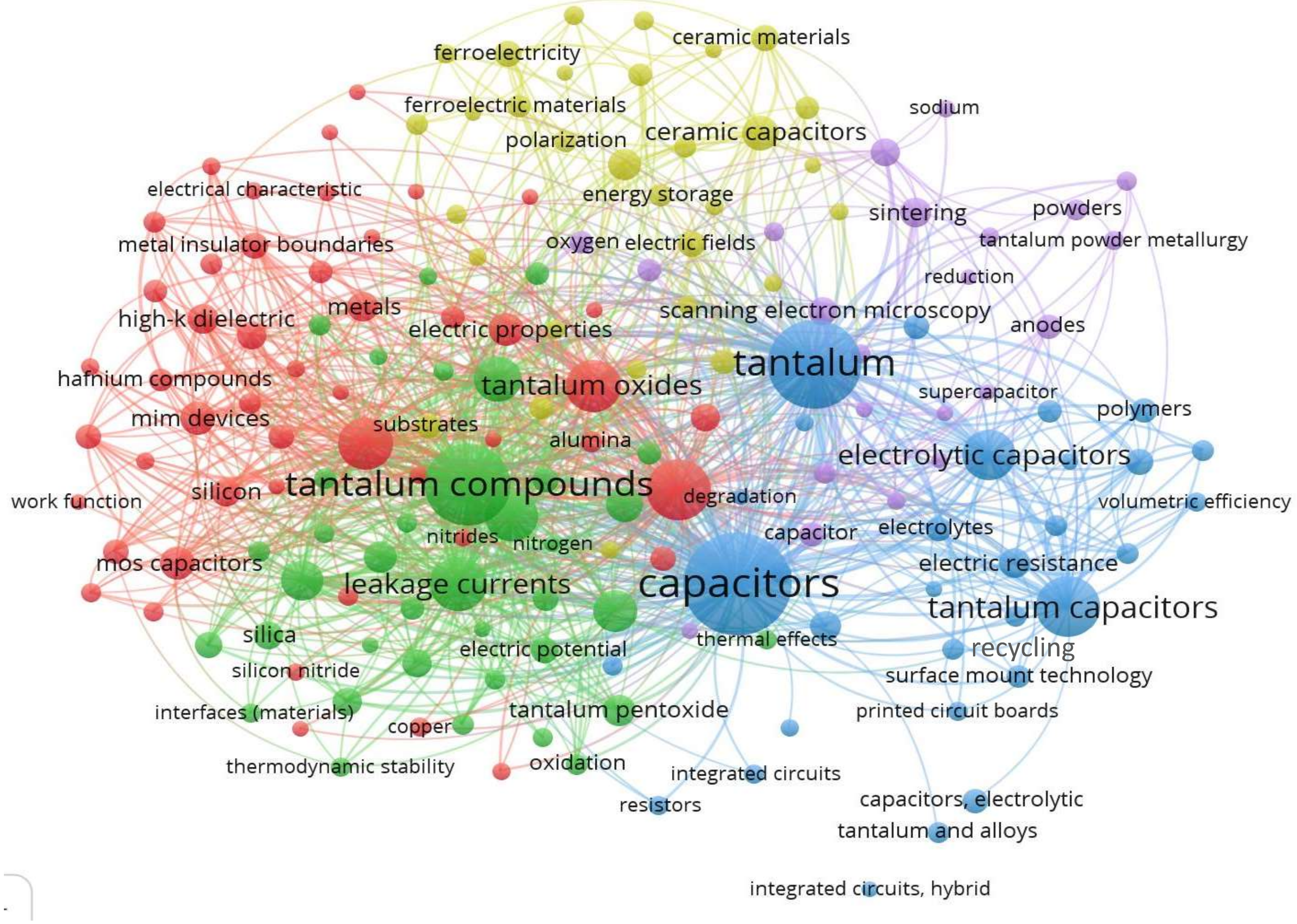

Figure 1.6 Network visualization for minimum co-occurrence as 20

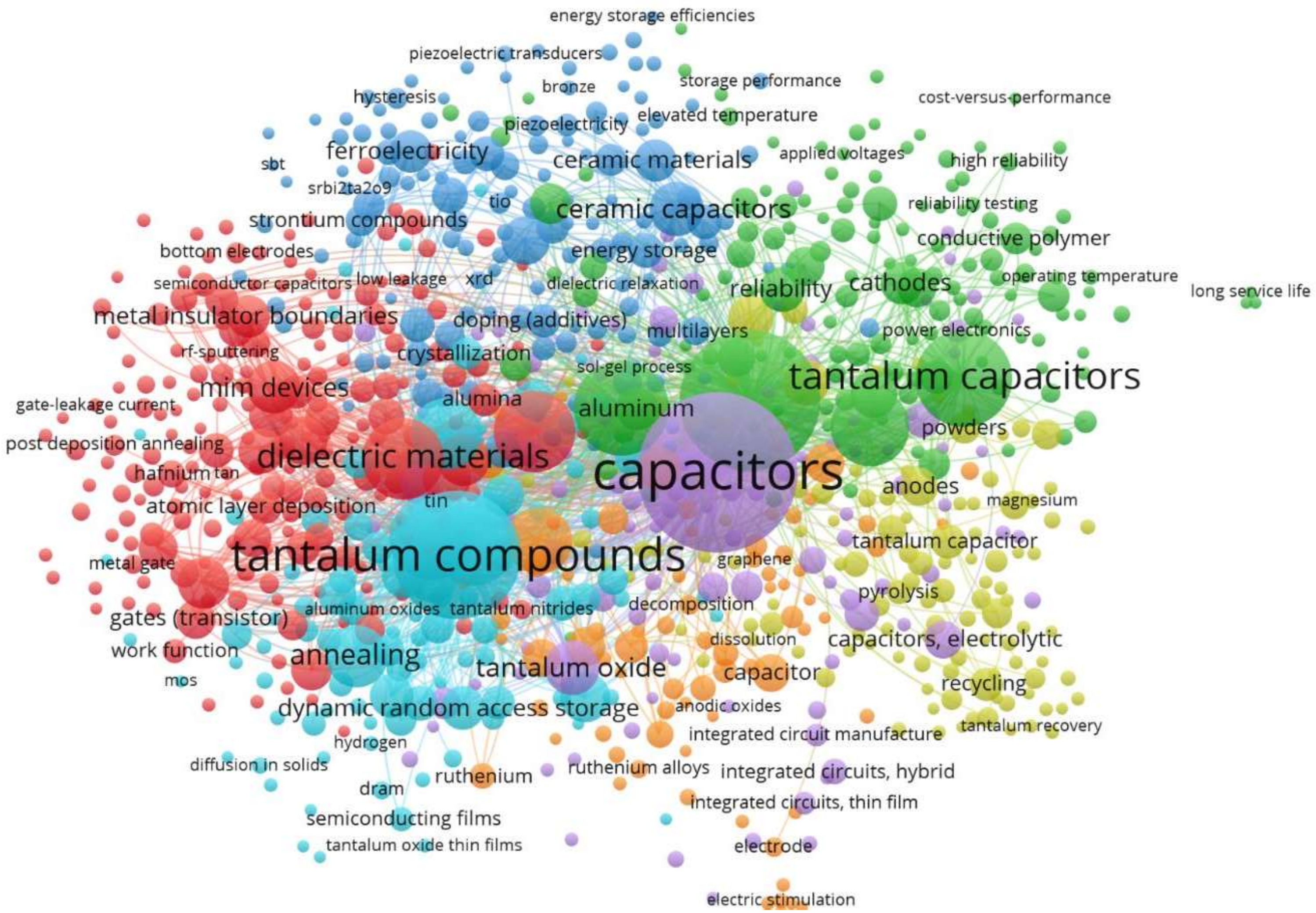

Figure 1.7 Network visualization for minimum co-occurrence as 5

1.5.2 Metal recovery from ECs from e-waste

Overall steps involved in recovery of metals from ECs present in e-waste is shown in *Figure 1.8* which are discussed in subsequent subsections.

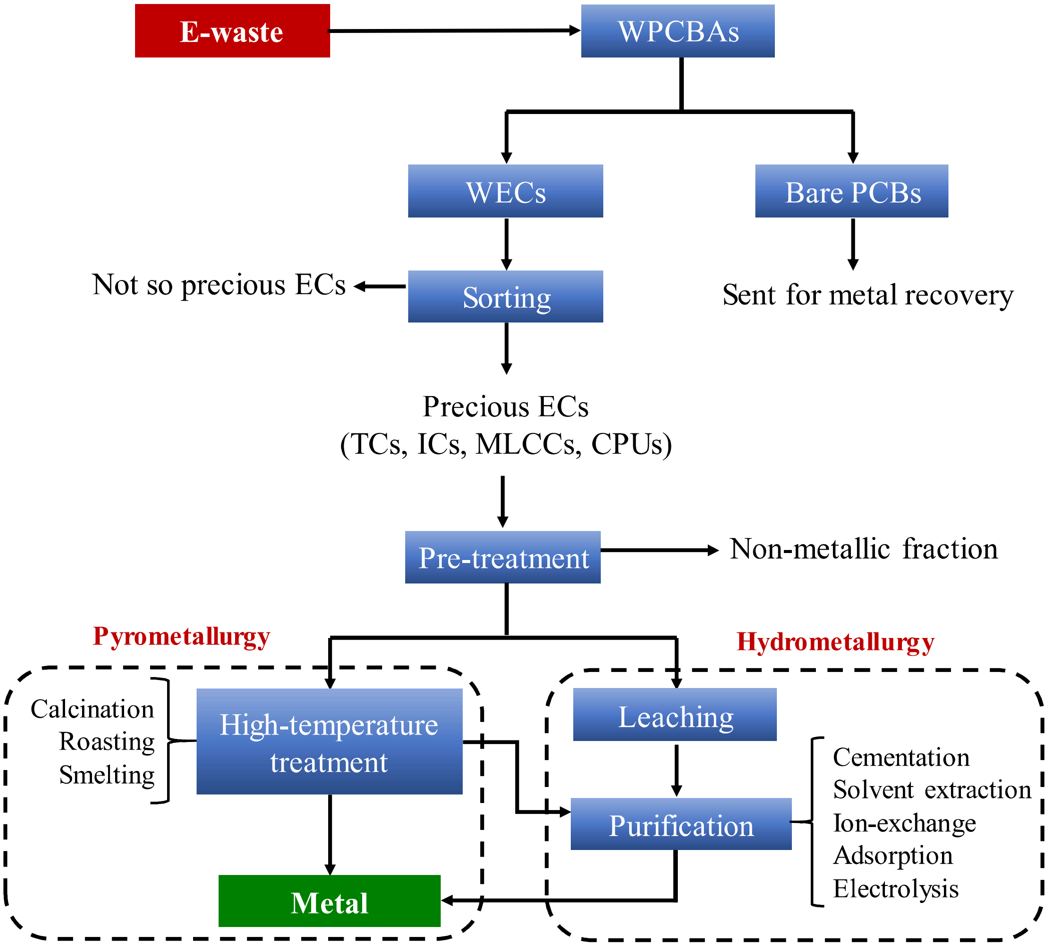

Figure 1.8 Steps in recovery of metal from WECs present in e-waste (WPCBAs- waste printed circuit board assemblies)

1.5.2.1 Liberation of PCBA

Liberation of PCBA is the 1st step in the recovery of metals from WEEE. Liberation allows isolation of PCBA which in turn result in greater accessibility and concentration of electronic components in waste streams. Different methods are employed for successful separation of PCBAs such as impact crushing (Bulach et al., 2018; Owada et al., 2012), immersion of electronic equipment in liquid nitrogen and subsequent smashing (Charles et al., 2020), automatic liberation using robotic arm (Noll et al., 2021), etc. Out of these, impact crushing is reported to be more efficient due to their flexibility with respect to feedstock and capacity.

1.5.2.2 Disassembly of ECs from PCBs

The liberated PCBA needs to be dissembled before subjecting it to the metal recovery treatment. Removal of electronic components is a pre-requisite for effective utilization of both bare PCBs and ECs. If ECs are not prior detached, it will enter into the mainstream recycling process and valuable metals present in it will be lost due to lower concentration of metals in it compare to other base metals in the bare boards. The undamaged ECs can be sorted to separate it from damaged one and allow it to be re-used (Debnath et al., 2016; Lee et al., 2012; Wu et al., 2022).Various processes are reported by different researcher to dissemble ECs from the bare PCBs which will be discussed in this section.

Disassembly of the component from PCBs can be performed in two ways viz. selective or simultaneous. In selective removal, individual assembly is identified by “look and pick” principle and subsequently dissembled and is employed in reuse oriented operations. On the other hand, simultaneous disassembly, based on “evacuate and lost” principle, is the process where all the components are simultaneously removed by subjecting PCBs to a heating treatment in the furnace. The process of simultaneous disassembly often results in higher cost, processing time, as well as higher probability of damaging the components (Chauhan et al., 2018; Kumari and Samadder, 2022).

Currently, different methods are used worldwide for disassembling ECs. The most commonly employed practice by developing countries in informal recycling sites is manual disassembly. used (Kumari and Samadder, 2022). In this practice, chisels, hammers, or cutting torches are employed for opening of solder joints to separate-out different ECs. Besides that, PCBA with more complicated structures are often subjected to burning and melting which causes pungent smell and toxic fumes, which leaves lethal impact on the human life as well as the environment (Duan et al., 2011). The negative impact of manual dismantling on human health and environment, the lower efficiency and higher labor cost prompted the development of mechanical disassembly process. which is more commonly employed in developed countries (Kumari and Samadder, 2022). Mechanical disassembly can be of fully automatic or semi-automatic. The automatic dismantling cell consists of an image processing "Vision System" which recognize the re-usable and hazardous components of PCBAs based on their shape and label on the parts and separate it out (Duan et al., 2011). A more flexible approach i.e., semi-automatic disassembly method was developed by Iji and Yokoyama (Iji and Yokoyama, 1997) for the removal of ECs from PCBs. The process uses the combination of heating system and external forces in the form of impact, vibration, or shearing force for the removal of ECs. Besides this, various laboratory scale methods have been proposed by different authors such as infra-red heating (Park et al., 2015) or electric heating tube, hot fluid as a heating medium (Zeng et al., 2013), chemical dissolution (Niu et al., 2017a; Verma et al., 2016) etc. which are outlined in *Table 1.2* with their advantages and limitations.

Table 1.2 Various reported methods for ECs dismantling with their advantages and limitations

Category	Method applied	Operating parameters	Advantages	Limitations	References
Mechanical dismantling	Manual dismantling	Manual removal using chisels, hammers, and cutting torches	Easier process Selective separation Low capital investment	Laborious work Time consuming Lower efficiency High labor cost	(Maurice et al., 2021)
	Surface Cutting Knife Dismantling	Automatic removal using surface cutting knife or blade	Low operating cost Disassembly rate is high	Efficiency is low compared to heating and chemical dissolution	(Lee et al., 2012; Wang et al., 2016)
Dismantling via a Heat Treatment	Crude Heating	Combine heating with mechanical treatment. Heat generation by means of electricity, gas torch, or wood fire.	High disassembly efficiency Higher solder recovery rate High thermal efficiency	High heating rate causes high cost Pollution Damage to ECs caused by heat absorbance Toxic fumes and waste generation	(Rocchetti et al., 2018)
	Infrared Radiators (IR)	Use of controlled infrared radiation to bring solder to the melting point.			(Park et al., 2015)
	Hot Air Heating	Melting of solder by hot air in combination with vibration and pulsed jet.			(Yang et al., 2017)
	Solder Bath Heating	De-soldering by implying molten solder in direct contact with ECs			(Wang et al., 2016)

	Hot Fluid Heating	Use of chemically inert hot fluid (hydrophilic ionic liquids, diesel, paraffinic oil or silicone oil) to melt solder.			(Zeng et al., 2013)
	Heated Centrifugation	Heating WPCBs followed by centrifugation to allow it to dismantle			(Zhou and Qiu, 2010)
Chemical Methods	Solder Dissolution	Dissolution of solder joints by employing an oxidizer (Ammonia based solutions, acids, ionic oxidizers, etc.)	Higher dismantling efficiency Reagents can be re-used	Liquid waste generation Required further dismantling treatment Longer time due to absence of heating	(Zhang et al., 2015; Zhu et al., 2012)
	Hydrothermal and Supercritical Fluids (SCF) Treatment	Use of sub- or super-critical water to oxidize organic matter or metals			(Niu et al., 2017)
	Dismantling via Epoxy Resin Treatment	Dissolution or decomposition of epoxy resin by using different organic solvents (DMSO, DMA, DMF, etc.)			(Verma et al., 2016a, 2016b)
High Voltage Electric Pulse	-	Employing high voltage electric shockwaves for fragmentation of WPCBs	Less manpower Higher treatment capacity Non-polluting	High cost Low energy efficiency	(Duan et al., 2015)

1.5.2.3 Metal enrichment

Once the ECs are separated from basal PCB, they are sorted and subsequently processed for metal recovery. The ECs which are most frequently considered for metal recovery are TCs, MLCCs, ICs, and CPUs. The 1st step in the recovery of metals from these ECs is *metal enrichment*. Metal enrichment is an important step to separate the unwanted metal/non-metals from the desired fraction and make it more amenable to further recycling steps. Different methods are employed for metal enrichment which includes: physical treatment, pyrolysis, and supercritical water treatment.

In physical treatment, there are two different steps. In the 1st step, the components undergo crushing and sizing to get the desired sized material. Then this fraction is subjected to 2nd step treatment such as magnetic separation (Fujita et al., 2014), gravity separation (Zhao et al., 2017), electrostatic separation (Niu and Xu, 2017), froth floatation (Wang et al., 2020), etc. The selection of individual process in the 2nd step depends on the type of impurities that needs to be separated and their characteristics. Even though physical separation procedures have a greater separation efficiency and produce less pollutants, the process is less appealing due to its high degree of noise and dust production.

Most of the ECs such as TCs, ICs, resistors, transistors, etc. contain a tightly covered epoxy mold housing forming the outer surface layer (Niu et al., 2017b; Ruan et al., 2017). Pyrolysis is the most advanced technique which are currently employed to decompose these complicated epoxy resin structure (Jie et al., 2008; Long et al., 2010; Sun and Qiu, 2011). Pyrolysis is the process where component is heated at high temperature (350-900°C) in an inert (N_2, Ar, He, etc.) or vacuum atmosphere. This facilitates the decomposition of mold resin, and consequently, three different products are generated i.e., oil, gas, and solid residue. It is reported that decomposition of organic takes place when the organics vapour pressure is more than the ambient pressure. The main factor leading to the decomposition of mold resin in pyrolysis is breaking and combining of chemical bonds of polymers based on the bond energy (Jiang et al., 2012; Niu et al., 2017b; Wang and Shi, 2006). More often pyrolysis treatment is coupled with subsequent physical and mechanical treatment such as crushing, screening, magnetic separation, etc. to get the desired end products (Niu et al., 2017b). The products of pyrolysis enrichment have a greater leaching rate in the succeeding wet process when compared to mechanical crushing and enrichment (Havlik et al., 2010). This pyrolysis process offers a significant advantage in terms of reduced environmental and economic impacts by eliminating liquid waste, effective utilization of gaseous by-products, and avoidance of toxic HCl and Cl_2. However, there are still a few challenges such as high temperatures, increased costs, volatile organic pollutants, etc., that must also be taken into consideration (Niu et al., 2017b, 2017c).

In addition to pyrolysis, technologies utilising supercritical fluids (SCF) have been utilized as high-efficiency methods for recycling complex or hazardous wastes without the risk of contaminating the air or water. Both supercritical water (SCW) and supercritical carbon dioxide are considered as extremely promising reaction media due to their ecological, nontoxic, and affordable qualities (Li and Xu, 2019). When operating at supercritical conditions, temperature and pressure have a key role in altering the physical and chemical characteristics of the SCF (J. Chen et al., 2022). Many researchers have employed SCW technology to decompose toxic organic waste (Gong et al., 2016; Wang et al., 2015). SCW physically and chemically exhibits characteristics different from the water at room temperature and normal atmospheric pressure. It provides water rich in hydrogen (H^+) and hydroxyl (OH^-) ions that act as an effective acid/base catalyst for organic reactions (Savage, 1999). SCW can effectively decompose mold resin due to free radical reaction under the optimum state of pressure, temperature, and time. The decomposition of organics becomes effective with increased temperature and time as the system energy is just enough to break the bonds of polymer and generate free radicals (Niu et al., 2017a). Besides several advantages of SCF technology, the industrial exploitation of this process is currently constrained due to the associated limitations such as equipment corrosion and the build-up of inorganic salts (Vadillo et al., 2013).

1.5.2.4 Recovery of metallic values

After the metal enrichment, the next step is *recovery* of target metals from concentrated fraction. A technology such as pyrometallurgy, hydrometallurgy, biometallurgy, or a combination of these can be used to recover metals.

Pyrometallurgy is the traditional method which has been successfully industrialized for recovery of valuable metals from e-waste. The process includes incineration, roasting, sintering, and smelting are under controlled high-temperature condition to recover the target metals from e-wastes (Gautam et al., 2022; Rao et al., 2020). The solid waste is usually heated using specialized incinerators, or plasma arc furnaces. The crushed scraps containing metals are volatilized under high temperature and the impurities are converted into slags to obtain coarse metal ingot (Kumari and Samadder, 2022; Zhang and Xu, 2016). There are successful pyrometallurgical methods which are being used throughout the world for processing various metals fractions, including the Noranda smelting process, Aurubis smelter, Umicore's Smelter, and Boliden Ronnskar Smelter (Cui and Zhang, 2008; Hagelüken, 2005; H. Wang et al., 2017). Pyrometallurgy mostly produces intermediate metals, which later need to be separated and refined by using different hydrometallurgical methods like leaching and electrowinning (Wu et al., 2022). Pyrometallurgical processes are used in industrialization because of their high economic value. However, high investment costs, energy requirements, loss of noble metal into slag, and the production of large amount of poisonous gases has always remained a challenge over the years that needs to be considered (Kumari and Samadder, 2022).

In contrast to pyrometallurgical processes, hydrometallurgical methods are much more flexible, easily controllable, suitable for small scale application with the potential to reduce the environmental impact (Gautam et al., 2022). In the hydrometallurgical process, the metallic fraction obtained after pre-processing is first subjected to leaching for preferential dissolution of target metal, producing a multi-metallic leach liquor. The choice of leaching reagent plays a pivotal role, and it should offer the desired selectivity towards the target metal under mild condition for the process to be environmentally and energetically efficient. Inorganic acid such as H_2SO_4, HNO_3, HCl (with or without oxidizing agents) are the most commonly employed lixiviants for base metals dissolution from WEEEs (Gontijo and Majuste, 2020; Tuncuk, 2019). Besides this, cyanide, aqua-regia, thiosulfate, and thiourea are extensively employed for precious metal dissolution (Behnamfard et al., 2013; Petter et al., 2014).

The pregnant leach liquor obtained after leaching contains heterogeneous mixture of elements. Selective separation of desired metal from this multi-metallic solution remains a major challenge. Various techniques such as solvent extraction, ion exchange, chemical precipitation, cementation, adsorption, polymeric membrane method, etc. are employed to concentrate the desired metal with high purity (Mir and Dhawan, 2022; Rao et al., 2020). The choice of individual purification process depends on the chemistry of the metallic solution, cost, and complexity of the process.

Various existing methods on recovery of metals from ECs using hydrometallurgical routes are summarized in *Table 1.3*.

Table 1.3 Summary on existing methods for recovery of metals from ECs

Raw material	Pre-treatment method	Leaching reagent	purification method	Metals recovered	References
Waste RAM device	Dismantling, Crushing, Milling	Step 1- H_2O_2+H_2SO_4 Step 2- I_2+ H_2O_2	-	Cu (98.73%), Au (99.98%) and Ag (96.90%)	(Tuncuk, 2019)
Waste CPUs and CPU connector pins	Comminution and sizing	Two steps For Cu: H_2SO_4 + H_2O_2; For Au: $CS(NH_2)_2$ + Fe^{3+} + H_2SO_4	-	Cu (90%), Au (69%).	(Birloaga et al., 2013)
Processor scrap	None	Partial oxidation using ammonium persulfate + O_2	-	Au (98%)	(Alzate et al., 2016)
CPU connector pins	Manual treatment using thermal blower and wood chisel	1st step: H_2SO_4 + H_2O_2, 2nd step: HCl + H_2O_2 3st step: HCl	-	1st step: Cu (71%), Ag (100%); 2nd step: Fe, Co and Ni (100%); 3rd step: Pb and Sn (100%)	(Gontijo and Majuste, 2020)
MLCCs	Crushing+ copper capture	HNO_3	Precipitation with NaCl (for Ag removal) + Electrodeposition (for Pd)	Pd (99.02%)	(Liu et al., 2020a)

MLCCs	Pulverization	HCl + HNO_3	Precipitation (for Ag) + Solvent extraction (for Cu) + Evaporation (for Pd)	Ag, Pd, Cu	(Panda et al., 2020a)
Waste CPUs	Crushing	Concentrated HNO_3+ Aqua regia	Removal of excess HNO_3 followed by gold precipitation with iron sulphate	Au (82.3%)	(Dehchenari et al., 2016)
Waste CPU sockets	Manual removal of plastic and steel shells + cutting and shredding	Slurry electrolysis (HCl+ NaCl + H_2O_2)	-	Au (95.73%), Cu (96.67%)	(Li et al., 2019)
Connectors and ICs	Pulverization	NaCN and m-nitrobenzene sulfonic acid sodium salt in distilled water	Adsorption+ burning, Ion exchange+ cementation/evaporation	Au	(Panda et al., 2020b)
ICs	Pulverization + gravity separation	HNO_3	Precipitation (Ag, Fe, and Ni), solvent extraction (Cu), cementation (Pb)	Ag (99%), Fe, Cu, Pb and Ni	(Panda et al., 2021)
MLCCs	Pulverization	Eutectic capture process	-	Cu-Pd-Ag alloy, Pb (100%), Ag (87.53%)	(Liu et al., 2020b)
Tantalum capacitor	Pyrolysis, crushing, grinding, magnetic separation	Pressure Leaching with HF	Solvent extraction+ precipitation + calcination	Ta (98%)	(Chen et al., 2019)

1.5.3 Tantalum recovery from WTCs

The general steps involved in recovery of tantalum from WTCs from e-waste is shown in *Figure 1.9*. Firstly, WPCBAs containing tantalum capacitors are liberated from different kinds of e-waste as mentioned in *Section 1.5.2.1*. WPCBAs are then processed by using the processes described in *Section 1.5.2.2* for the detachment of different ECs from which tantalum capacitors are sorted out based on visual identification. These tantalum capacitors are subsequently treated by different physical and chemical treatment for recovery of tantalum and other metals which will be discussed in the subsequent sub-section.

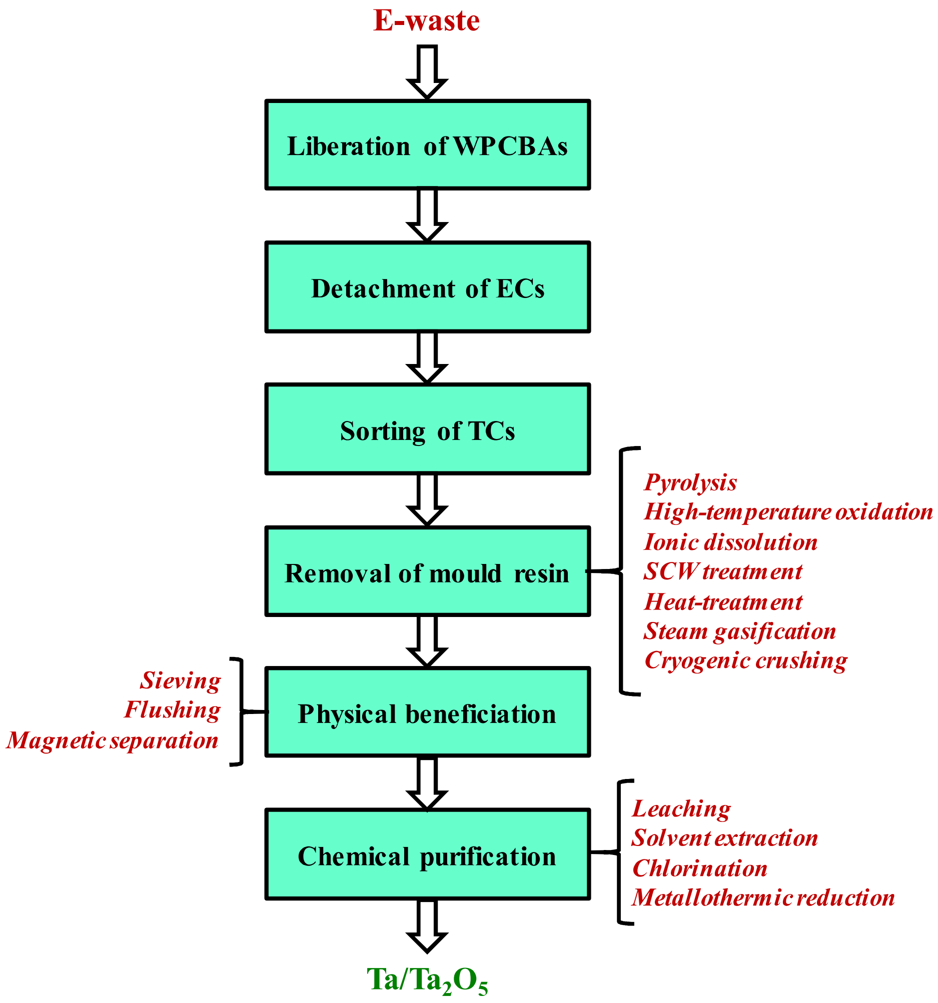

Figure 1.9 Steps involved in recovery of tantalum from WTCs from e-waste

1.5.3.1 Pre-treatment of capacitors

In tantalum capacitor, the metallic parts are surrounded by outer mold housing that is composed of phenolic novolac resin, silica, epoxy resin, and flame retardants (Mineta and Okabe, 2005).The presence of silica in the outer mold resin of capacitors presents a major bottleneck for the efficient recovery of tantalum due to their similar chemical reactivity (Bastin et al., 2020). Therefore, removing encapsulated mold resin is a prerequisite for the effective recovery of tantalum (Chen et al., 2019). The methods that are reported in previous studies for separation of mold resin are listed in *Table 1.4*.

Mineta and Okabe, 2005 developed high-temperature oxidation treatment for decomposition of mold resin from tantalum capacitors. The temperature of oxidation played a key role in separating organic mold resin from the inner tantalum anode. When the oxidation temperature was low, then the tantalum electrode was collapsed along with the outer casing. Also, at higher oxidation temperatures, some SiO_2 lumps clumped by molten silver. Consequently, in both cases, further separation of tantalum became difficult, and total metallic recovery fell off. This simpler process could effectively decompose exterior mold resin and recover metallic tantalum. However, traces of silica entrapped during the oxidation treatment could not be removed. So to get high purity tantalum, an additional process is required (Mineta and Okabe, 2005).

Von Brisinski et al., 2014 proposed another method where all the components of WTCs except tantalum anode were dissolved chemically using the $AlCl_3$ ionic liquid. This approach is less appealing, though, due to the lower dissolution efficiency and higher ionic liquid cost (Von Brisinski et al., 2014). In another study Katano et al., 2014 (Katano et al., 2014) developed a new scheme for decomposition of mold resin using steam gasification with sodium hydroxide. Incorporation of the capacitor into the fused salt led to its dissolution in distilled water. The resultant capacitor was then filtered and sieved to obtain inner tantalum compact. Lower reaction temperature and pressure, cheaper reagent, and trapping of generated halogen gas by sodium ion in sodium hydroxide (NaOH) is some of the advantages of this method.

For the decomposition of mold resin from WTCs, pyrolysis is the most popular and widely used method (Xue et al., 2015; Zhou et al., 2010). A number of authors have reported pyrolysis treatment for mold resin removal where decomposition is carried out at different temperatures, depending on the stability range of organic matter, determined by thermogravimetric analysis. WTCs are heated under pre-determined condition of temperature and time in different atmosphere viz. argon (Niu et al., 2017b), nitrogen (Chen et al., 2019), or vacuum (Chen et al., 2018; Niu et al., 2020). It is reported that thermal decomposition of organics occurs in two major steps at different temperature intervals. An increase in the heating rate shifts the decomposition to higher temperatures because of the hindrance of diffusion of the volatiles. Vacuum pyrolysis has an advantage over other process due to faster pyrolytic reaction rate of organics, lower temperature, and higher organic removal efficiency. After pyrolysis, resultant oil and gas could be successfully recycled and used as energy products. Whereas, the inner tantalum rich-product is sent for subsequent metal recovery.

Besides this, some other method including heat-treatment (Fujita et al., 2014), SCW technology (Niu et al., 2017a) have been employed in laboratory scale with varying degree of success. Recently (Xia et al., 2021) proposed a newer concept for removal of mold resin using cryogenic crushing followed by alkaline calcination. After refrigeration treatment, the TCs became brittle which was crushed and calcined using NaOH to remove silica and other organic matter. Although the method appears to be efficient for removing organic matter, it is constrained in some ways by the cost of multi-step treatment and handling problems associated with liquid nitrogen treatment.

Table 1.4 Summary of existing methods for removal of mold resin from WTCs

Initial material	Pretreatment method for mold resin removal	Operating condition	Remarks	Reference
Capacitor scrap	High-temperature oxidation	1150 K for 30 min in air	Several steps required Energy consuming process Traces of silica entrapped during the oxidation treatment could not be removed	(Mineta and Okabe, 2005)
WPCBs	Heat treatment	723-773 K in air	Efficiency of the process is low	(Fujita et al., 2014)
Tantalum capacitor	Steam gasification	Using NaOH at 530°C for 5 min	Lower reaction temperature and pressure, Cheaper reagent	(Katano et al., 2014)
Tantalum capacitor	Pyrolysis	Argon atmosphere at 550°C temperature for 30 min	High temperature requirement Increased cost Vacuum pyrolysis leads to faster pyrolytic reaction rate of organics, with reduced temperature, and higher organic removal efficiency	(Niu et al., 2017b)
Tantalum capacitor	Pyrolysis	Vacuum environment at 425°C temperature, 50 Pa pressure for 30 min		(Chen et al., 2018)
Tantalum capacitor	Pyrolysis	N_2 atmosphere at 600°CC for 10 min		(Chen et al., 2019)

Tantalum capacitor	Cryogenic crushing + Alkaline calcination	Refrigerated in liquid nitrogen for 10 minutes with a solid to liquid ratio of 1 g:5 mL followed by calcination using NaOH at 700°C	Multi-step process Effective separation of organic matter containing silica	(Xia et al., 2021)
Tantalum capacitor	Ionic dissolution	Dissolution at 150°C in Lewis acidic (34 mol % dialkylimidazolium halide, 66 mol % $AlCl_3$) and Lewis basic (66 mol % dialkylimidazolium halide, 34 mol % $AlCl_3$) mixtures	Costlier process Origination of health hazardous halogen compounds	(Von Brisinski et al., 2014)
Tantalum capacitor	SCW treatment	SCW oxidation (SCWO- mixing a definite quantity of H_2O_2) treatment under the oxidizing condition and SCW depolymerization (SCWD) treatment under reducing condition , Heating rate-20°C/min	Incomplete decomposition of organics High temperatures and pressures required	(Niu et al., 2017a)

1.5.3.2 Chemical and metallurgical methods of purification of tantalum

After removal of mold resin by thermal, chemical of mechanical treatment, as mentioned in *section 1.5.3.1*, the resultant product needs to be physically treated to get the desired product required for chemical recovery. For this, crushing, sieving and flushing is the most commonly employed physical beneficiation methods to separate the SiO_2 from the product of pyrolysis (Chen et al., 2019) and high-temperature oxidation (Bastin et al., 2020; Mineta and Okabe, 2005). Subsequently, to separate the iron and nickel terminals, magnetic separation is used (Niu et al., 2020, 2017d). The product thus obtained is suitable to process by chemical recovery techniques. Various chemical methods used in the previous studies for the recovery of tantalum is listed in *Table 1.5*.

In the case of hydrometallurgical route of recovery, the target metal is selectively dissolved in the solvent and then processed by different purification methods for subsequent metal recovery. However, leaching of tantalum is not as simple as other base metals. Fluoride-based lixiviant, which have a high solubility for the tantalum, are the most commonly employed for dissolution of tantalum (Yang et al., 2018). The acidic properties of tantalum oxide, causing its poor dissolution in non-fluoride mineral acids as compared with other d-block elements under extreme conditions of temperature, pressure, and concentration (Theron et al., 2011). Chen et al., 2019 used pyrolysis for decomposition of mold resin followed by pressure leaching using hydrofluoric acid to dissolve tantalum and manganese and finally solvent extraction to recover tantalum from the solution (Chen et al., 2019). However, use of such harsh condition poses several health and environmental hazard (Nguyen and Lee, 2019). Furthermore, use of fluoride media imposes some practical limitations too due to its highly corrosive behaviour, making it suitable only for high-grade Ta-concentrate as it tends to dissolve too much quantity of gangue (Shikika et al., 2020; Wang et al., 2009). The use of other fluoride-free acidic leachate was examined by different researchers, however, a very low solubility of tantalum was found (Baba et al., 2018; S. Ayanda and A. Adekola, 2012; Theron et al., 2011). Besides this, alkaline lixiviant showed promising results to extract tantalum from primary ore, eliminating fluorine-based pollutants (G. J. P. Deblonde et al., 2019; Ghambi et al., 2021; Kinsman et al., 2020; Wang et al., 2009; H. Zhou et al., 2005).

To avoid this difficulty, researchers have often recovered tantalum in the solid residue while dissolving other metals into the leach liquor. Matsuoka et al., 2004 and Mineta and Okabe, 2005 used nitric acid leaching for dissolution of impurities followed by magnesiothermic reduction to obtain metallic tantalum (Matsuoka et al., 2004; Mineta and Okabe, 2005). In another approach, Orlov and Kiselev, 2012 treated tantalum anode with mixture of 1) HCl and H_2O_2 and 2) H_2SO_4 and H_2O_2 to decrease its manganese content. Presence of H_2O_2 determined the leaching rate of manganese rather than the concentration of acid (Orlov and Kiselev, 2012). Piotrowicz and Pietrzyk, 2016 used nitric acid to get rid of silver layer from tantalum anode. The author noted a remarkable resistance to manganese oxide dissolution in nitric acid media. After leaching, the resulting residue was treated by oxidation and thermic reduction using magnesium and aluminium to produce the desired end product (Piotrowicz and Pietrzyk, 2016). Similarly, Xia et al., 2021 used nitric acid for dissolution of silver from the product obtained after cryogenic treatment and alkaline calcination. Along with silver, remaining nickel and iron also entered into the leach liquor leaving high-purity tantalum into the residue (Xia et al., 2021).

Besides this, chlorination is proven to be effective method for purification of tantalum (Niu et al., 2020, 2017d). Niu et al., 2017c subjected the product obtained after pyrolysis and megnatic separation to chlorination using $FeCl_2$. It was seen that chloride metallurgy could selectively extract tantalum from the residue by reacting with $FeCl_2$, according to the reaction shown below (*Eq. 1.1*).

$$2Ta(s) + 5FeCl_2\,(s, l) = 2TaCl_5\,(g) + 5Fe\,(s)\ (T>380°C) \qquad (1.1)$$

As the boiling point of $TaCl_5$ is less (234°C), it was evaporated into the gas phase at chlorination temperature and separated by condensing into the condensation zone (Niu et al., 2017d). Similar results were reported by Chen et al., 2022 when the product of pyrolysis, constituting tantalum, graphite and AgCl, was treated with $FeCl_2$ at 450°C for 3 h. Chlorination followed by condensation led to the desired end product of high purity $TaCl_5$ (99%) with a tantalum recovery rate of 94% (Chen et al., 2022).

Table 1.5 Summary on various existing methods of recovery of tantalum from tantalum capacitor scrap

Initial material	Pretreatment method	Recovery methods	% recovery	Reference
Capacitor scrap	Oxidation, magnetic separation	HNO_3 leaching followed by magnesiothermic reduction	90-92%	(Mineta and Okabe, 2005)
TCs	Pyrolysis, magnetic separation	Chloride metallurgy	93%	(Niu et al., 2017d)
TCs	Pyrolysis, magnetic separation	HF leaching followed by solvent extraction, stripping and precipitation	98%	(Chen et al., 2019)
TCs	Cryogenic crushing, magnetic separation	Alkaline calcination followed by water and HNO_3 leaching	96.72%	(Xia et al., 2021)
WTCs	Milling	Bioleaching	<1%	(Kucuker et al., 2018)

TCs	Pyrolysis, magnetic separation	HCl leaching followed by chloride metallurgy	94%	(Chen et al., 2022)
TCs	Pyrolysis, magnetic separation	Corona electrostatic separation	~97%	(Niu et al., 2017e)
WEEEs	Crushing/Grinding	Leaching with HNO_3 followed by oxidation and thermic reduction with Al and Mg	57%	(Piotrowicz and Pietrzyk, 2016)
PCBs	Pyrolysis, crushing, sieving	HNO_3 leaching	-	(Bastin et al., 2020)
TCs	Pyrolysis, grinding, sieving	H_2SO_4 leaching	-	(Piotrowicz and Pietrzyk, 2019)

1.6 Research gaps

After completing the literature review on recovery of tantalum from electronic waste specifically from waste tantalum capacitors, many gaps have been identified, providing research directions for the present work, which are discussed below.

1. To address the issues of potential supply shortage, supply risk in the future, price, dissipative losses, sustainability, economic concerns, and future demand, a better understanding of the flow of tantalum through the whole supply chain, i.e., from mining to manufacturing, processing, consumption, re-use, recycling, and the discard is essential (Bloodworth, 2014). A few attempts have been made in the previous research work to develop an understanding of tantalum flow (Achebe, 2016; Cunningham, 1998; Deetman et al., 2017; Nassar, 2017; Peiro et al., 2013; Yen et al., 2016). However, these studies are either limited to a particular country or are confined to few life-cycle stages

of tantalum. None of the article provided a quantitative estimation on global waste generation through-out the life cycle stages of tantalum and associated economic loss with the amount of metal going into discards.

2. The presence of silica in the outer mold resin of capacitors presents a major bottleneck for the efficient recovery of tantalum due to their similar chemical reactivity (Bastin et al., 2020). Therefore, silica should be removed efficiently to recover high-purity tantalum. All the methods reported in the previous studies for removal of silica (*Table 1.4*) are tedious, costlier, energy-intensive, and compromise on purity of the end-product. Therefore, an efficient and cost-effective pre-treatment step is required for successful separation of silica from tantalum.
3. It was further observed that there are very limited research articles available on recovery of metals from WTCs (*Table 1.5*). Therefore, more research work is needed in this area to provide an economically and environmentally significant process for tantalum recovery.
4. The various methods that are proposed on previous work are only limited to recovery of single metal i.e., tantalum. However, the other metals which are present in the tantalum capacitor, and are economically and strategically significant are often neglected. Therefore, an integrated method needs to be developed for sequential recovery of metals from WTCs.
5. Cost is the single most important factor which is considered for any process to be commercially viable. However, all the studies reported in the past studies are limited to lab scale only and did not provide any estimation of cost for the proposed process. Hence, economic feasibility study is required to understand the industrial viability of the process.

1.7 Research objectives

Based on the above-mentioned research gaps, the following objectives were set in this work:

1. **To determine flow and stock of tantalum through its entire life-cycle stages.**

   A quantitative model on global tantalum flows is developed to build a comprehensive knowledge on stock and flow of the metal through its entire life cycle with special emphasis given on waste flows. In addition, an economic evaluation of discarded Ta-containing e-waste was done.

2. **To separate silica in the pre-processing stage.**

   A simpler and energy-efficient method was developed to separate silica, along with the organic matter, in the pre-processing stage without letting it mix with the inner tantalum anode.

3. **To recover high-purity tantalum using hydrometallurgical route.**

   A two-stage leaching method was developed for recovery of tantalum from waste tantalum capacitor. Various leaching parameters such as time, temperature, concentration of leaching reagent, and pulp density were optimized to maximize the recovery of the target metal (tantalum) with desired purity.

4. **To recover other valuable metals such as silver, manganese, and nickel.**

   After successfully recovering tantalum, the solution obtained after 1st stage leaching contained significant amount of manganese and nickel. This leach liquor was therefore treated by solvent extraction for selective separation of manganese. Parameters such as concentration of organic matter, pH of the aqueous solution, temperature, time, and organic to aqueous ratio was optimized to choose the most effective parameters for separation of manganese and nickel. In addition to that, the non-metallic-rich fraction separated after pre-processing contained significant amount of silver. This fraction was treated further for recovery of silver.

5. **To conduct cost benefit analysis to estimate the industrial viability of proposed recycling route.**

   Lastly, after finishing the experimental process, cost benefit analysis (CBA) was conducted to get the estimate of total recycling cost and profit that can be achieved by treating the tantalum capacitor waste on an industrial scale.

1.8 Organization of the thesis

The overall thesis is divided into 7 chapters followed by scope of future work, references, and publications/conferences details. A brief about each chapter is discussed in the following paragraphs.

As seen in the previous sections, **Chapter 1** presented the background related to e-waste, printed circuit board assemblies, tantalum in electronics, and outlined various opportunities of metal recovery especially tantalum from the waste tantalum capacitors mounted on bare PCBs. The literature falling in the domain of metal recovery from various ECs were extensively reviewed, with special emphasis given to WTCs recycling. Based on the literature study, the existing research gaps was identified, on the basis of which the objectives of this study was drawn.

After setting the objectives of this work, the experiments were designed. **Chapter 2** gives a detailed description on materials and methods employed for recovery of target metals. Initially, details on various raw material collection required for conducting the experiments is given. The experimental set-up used during the experiments is then described in detail. The various characterizations and chemical analysis methods used to analyse the liquid and solid samples after each stage of treatment such as X-ray diffraction analysis (XRD), scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS), Atomic absorption spectroscopy (AAS), inductively coupled plasma-mass spectroscopy (ICP-MS), and Fourier transform infrared spectroscopy (FT-IR), are also briefly discussed.

Results of this wok in divided into four chapters from chapter 3-6. In **Chapter 3**, a quantitative model on global tantalum flows was developed to build a comprehensive knowledge on stock and flow of the metal through its entire life cycle with special emphasis given on waste flows. In addition, an economic evaluation of discarded Ta-containing e-waste was done to estimate the potential of tantalum recovery from end-of-life resources. Based on the results of the study, possible future solution is discussed for planning on supply security, resource conservation, and economic gain.

In **Chapter 4**, results of tantalum and silver recovery from waste tantalum capacitors is described. Firstly, the results of pre-processing (to separate inner metallic fraction and outer encapsulated non-metallic fraction) and characterization of each individual components/layers of WTCs are presented in detail to understand it's internal structure. After this, the outcomes of tantalum recovery are described for each chosen recovery pathways i.e., alkaline and acidic leaching route. Findings of optimization study in case of acidic leaching route is also given. Kinetic study results are discussed to understand the leaching mechanism and determine the activation energy for reaction. Finally, the outcomes of silver recovery are described in detail.

In **Chapter 5**, results of manganese and nickel recovery are described in detail. The pregnant leach liquor obtained after acidic leaching route was processed for selective manganese extraction from other metals, particularly nickel via the solvent extraction route. The performance of two distinct organophosphorous extractants was examined by altering a series of parameters to determine the best conditions for maximum manganese recovery.

Lastly, after finishing the experimental process, cost benefit analysis (CBA) was conducted to get the estimate of total profit that can be achieved by treating the tantalum capacitor waste in industrial scale whose results are presented in **Chapter 6**. The total cost (capital cost+ recycling cost) for a month (220 tons/day/shift for 3 shift a day) of running the recycling facility with proposed recycling route and revenues that can be achieved with the output products/by-products were estimated to assess the profitability. Additionally, sensitivity analysis results are presented to determine the impact of most critical factors on the profit.

At the end, **Chapter 7** embodies the major conclusions drawn from current research work. Following this, the scope of future work, bibliography related to the cited references, and publications/conferences details are given

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