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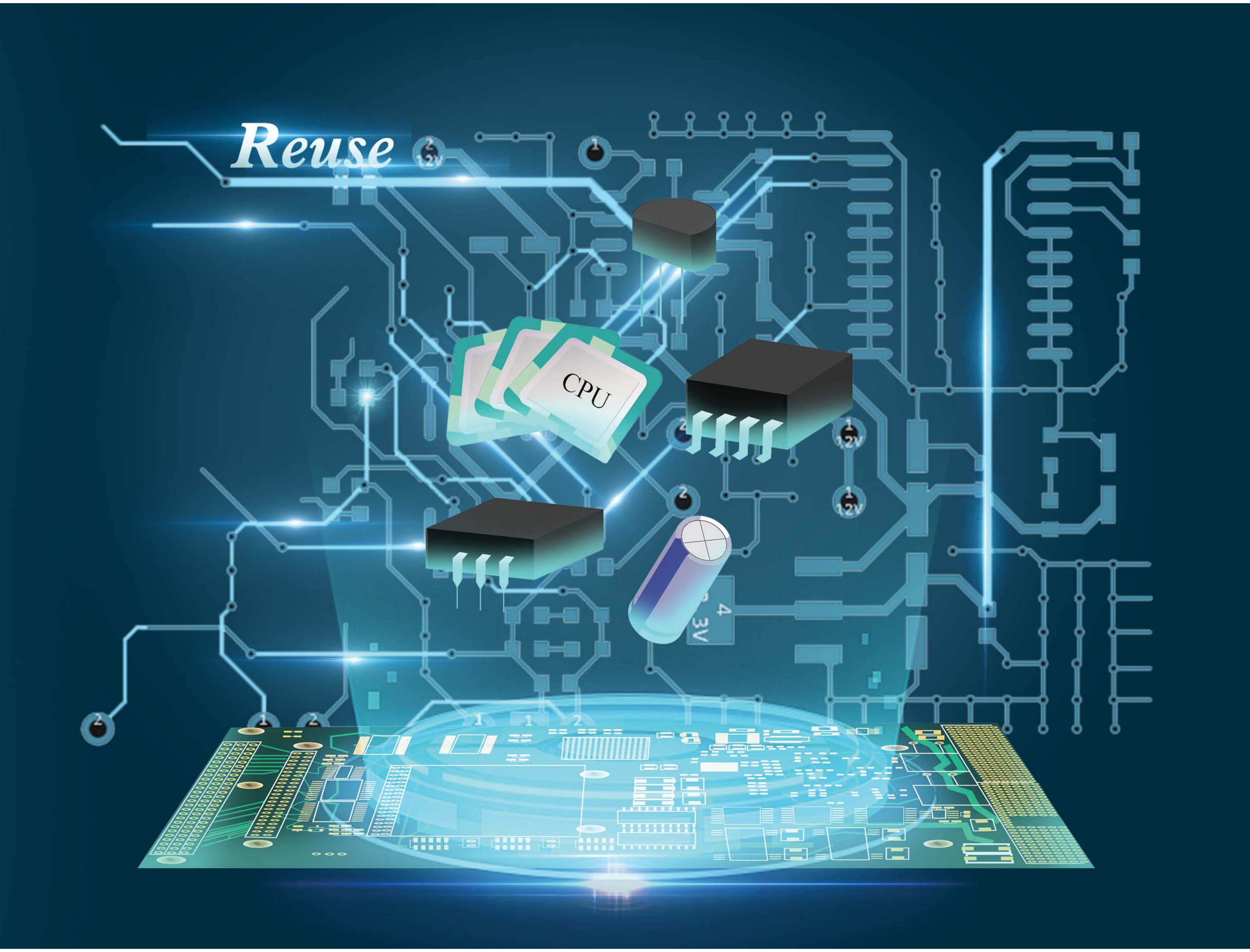

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CRITICAL REVIEW
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The reuse of electronic components from waste printed circuit boards: a critical review

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As a key component of all electrical and electronic equipment, waste printed circuit boards (WPCBs) are an important target for waste electrical and electronic equipment (WEEE) treatment. Over the years, many researchers have developed a variety of means to recycle WPCBs. However, current research into the reuse of undamaged electronic components (ECs) is not as extensive as that conducted on recycling of metals from WPCBs. In fact, most of the ECs on WPCBs still have a high level of functionality and usability at the time of their recycling. Reusing "obsolete ECs" that are far from reaching the end of their useful life will help to mitigate the excessive carbon emissions associated with the mass manufacture of components, save scarce resources and eliminate potential exposure to hazardous substances. Therefore, we will discuss the current recycling system of WPCBs in different regions of the world, and then introduce the research progress of recycling of ECs on WPCBs from both theoretical and applied aspects. First, this paper analyzes 1788 related literature studies through CiteSpace and it was found that although there is more research on recycling of WPCBs in developing countries such as China and Indonesia, there is still a gap between it and practical industrial applications. The paper then presents the theoretical foundation and research progress of the research related to the reuse of ECs. More efficient and less damaging disassembly methods imply higher reuse rates and higher economic efficiency. Choosing the appropriate disassembly method according to different board types is the first and key step in reusing ECs on WPCBs.

Environmental significance

As technology advances, electronic waste has become an urgent problem worldwide. Compared to ordinary solid waste, e-waste is more complex in composition and contains a large number of carcinogenic substances. The process of treating and disposing of electronic waste such as printed circuit boards is therefore of great significance for the environment and human health. Reuse is always considered preferable to material recovery in the waste hierarchy. Reusing ECs as an effective means of a circular economy not only reduces costs, reduces further consumption of resources using new products and mitigates potential environmental pollution from WEEE disposal, but also facilitates a shift to a green recycling scene in the waste management sector.

1 Introduction

In 2019, the world generated a striking 53.6 million metric tons (Mt) of e-waste. The E-waste Statistics Partnership predicts that the annual global volume of waste electrical and electronic equipment (WEEE) produced will reach an amount of 74.7 Mt in 2030.[1] It is clear that overproduction of WEEE has become an urgent problem worldwide.[2] On the one hand, WEEE contains a large number of components that can have harmful effects on the environment and humans, and its indiscriminate handling and informal recycling can make WEEE a global public and environmental health problem.[3–6] On the other hand, due to its physical properties, WEEE is ideally suited for recycling and can bring great benefits when recycled.[6,7] This makes WEEE an attractive secondary resource and environmental pollutant at the same time.[8] Waste printed circuit boards (WPCBs), which contain a large number of high-value components and toxic substances, are a critical component of all EEE and an important target for WEEE disposal.[9–11] In terms of overall composition, WPCBs typically contain various types of bare boards and many electronic components (ECs). ECs on WPCBs usually contain capacitors, relays, resistors, integrated circuits, *etc.*[12] The composition and concentration of these two types of materials vary greatly, which undoubtedly increases the complexity of the recycling process.[12–16] In terms of material composition, a PCB comprises an insulating non-metallic polymer substrate (resin), metal foil, laminated layers, and

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electronic components,[17] which are complex in composition and nature.[18]

The common recycling process of WPCBs is shown in Fig. 1. In the pre-processing stage, the ECs are removed from the surface of the WPCBs.[19] WPCBs are then divided into bare boards and ECs for the deep processing step.[20] In the deep treatment stage, researchers have developed mechanical,[21] pyrogenic,[22] pyrolysis,[23] wet,[24–26] bioleaching,[27–29] and many other methods for resource recovery of WPCBs. For example, Wang *et al.*[30] proposed a process to recover copper from PCBs by froth flotation and oxidative leaching to increase the copper grade from 38.70% to 68.34%. Driven by legislation and economics, the WEEE recycling industry continues to increase recycling rates and reduce the environmental impact of WEEE,[31] and it has been reviewed in detail by a large number of researchers.[32–38]

However, a more efficient approach is to reuse WEEE or its subcomponents.[31] The process of extracting valuable metals from WPCBs often results in serious secondary contamination.[9,39] Pokhrel *et al.*[40] found that the combined environmental change impact of recovering various metals from WPCBs, except Au, was higher than that of the mineral mining process. Iannicelli-Zubiani *et al.*[41] evaluated the process of treating 100 kg of WPCBs using hydrometallurgy and found that the process had an impact on global warming (GWP100a) of up to 7.02×10^2 kg CO_2 eq. Compared to material recovery, reusing refurbished and recycled components in reworked or new products can reduce costs and develop new business areas, can reduce further consumption of resources by new products, and can reduce land occupation.[42] By recycling and reusing, potential environmental pollution from WEEE can be reduced or mitigated, while also achieving the goal of a "second life" for WEEE.[39,43] European waste electrical and EEE systems have taken steps to encourage WEEE reuse.[44] In conclusion, reuse is always considered preferable to material recovery in the waste hierarchy.[45] Obsolete and discarded PCBs extracted from WEEE can be laddered and installed in "high-tech" toys.[46] Some researchers[44] have shown that, under certain scenarios, reusing PCBs in certain household appliances results in lower environmental impacts throughout the life cycle of reused EEE compared to new EEE, and can yield better economic benefits. In addition to utilizing the entire WPCB, the ECs on its surface can also be reused. Typically, there is a significant gap between the maximum technical life of an electronic product and its actual use. According to the lapse rate "bath curve" proposed by Peter[47] and others, ECs are at their optimal period of stable operation when WPCBs are discarded. In other words, many ECs are still functional and useable when disposed of as WEEE. Conti and Orcioni[39] argued that well redesigned electronic equipment and reuse of components can improve the reliability of the equipment, in addition to reducing waste. Therefore, it is feasible to reuse the high-value components on WPCBs.[12,48,49] In addition, the bare boards after disassembly of ECs can be used as novel environmentally friendly catalysts for the degradation of certain pollutants.[50,51] Reuse of components, as an effective way to recycle resources, not only has significant carbon reduction benefits, but is also an effective way to transform production methods for low carbon industries. Reusing "obsolete components" that are far from reaching the end of their useful life will help to alleviate the excessive carbon emissions caused by the mass production of ECs to a certain extent. However, the current research on reusing undamaged ECs from WPCBs (*i.e.*, the red circled part in Fig. 1) is not as extensive as the research on metal recycling. Most of the studies focus on bare plates with ECs already removed, or ECs that are also directly and coarsely crushed to recover the major elements, with the rest of the elements flowing to waste or being diluted in ash, which does not represent the real situation of WPCBs.[12,52,53] In summary, there is an urgent need for the WPCB recycling industry to shift to reuse and remanufacturing scenarios.[54]

In order to gain an understanding of the trends in the field related to the reuse of WPCBs, big data analysis was performed using CiteSpace software. CiteSpace is a Java platform-based visual scientific measurement software developed by Chen[55] in 2003 and has been applied in many scientific disciplines.[56] The software is designed to understand areas of knowledge from the large body of scientific literature and is one of the scientific

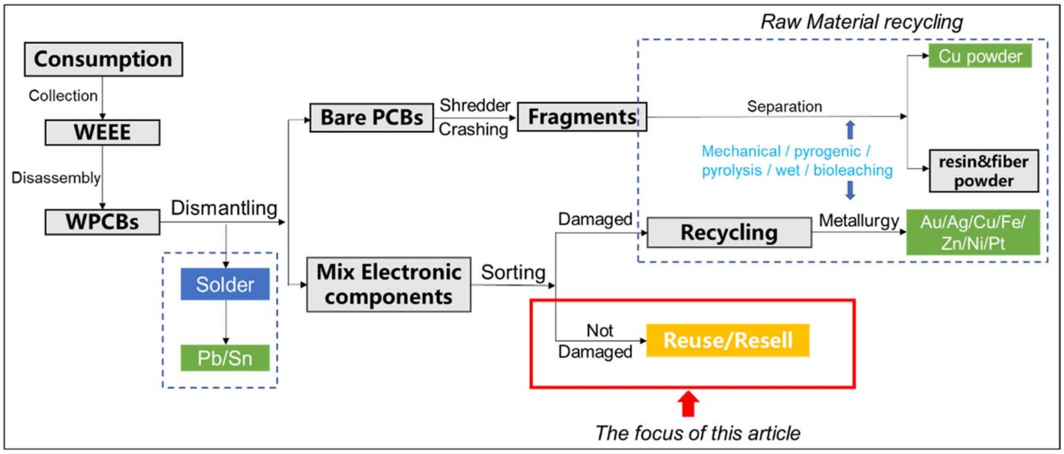


Fig. 1 WPCB recycling flow sheet.

mapping tools based on Web of Science and Scopus data,[57,58] making it very suitable for analyzing the research literature from the WOS database. Based on co-citation analysis, CiteSpace allows visualizing trends and fundamental changes in research content over time.

The purpose of this paper is to introduce the progress of the theory and technology of WPCB resource development, focusing on the theoretical basis and research progress of reusing ECs. Although a more detailed review of techniques for disassembly of ECs has been conducted by some researchers,[59] the focus of their studies has been on disassembling ECs to facilitate the extraction rate of subsequent metals. Therefore, the focus of this study is on the reuse process of ECs, not only the disassembly process of ECs.

2 Materials and methods

The literature for this review study was mainly obtained from the Web of Science database and the Chinese National Knowledge Infrastructure database. It mainly introduces the current situation of the practical application of reusing ECs and recycling treatment of WPCBs in different regions of the world from the macro aspect and introduces the current research status of its theory and technology in recent years from two aspects of the micro aspect. In the third part, CiteSpace software is used to obtain the research trends of recycled WPCBs in various regions of the world through big data analysis. Then the current status of several typical countries in terms of their practical applications is analyzed based on the literature and information from the internet. The fourth part discusses the theoretical basis of research and development in reusing of ECs from three aspects: common disassembly techniques, welding methods of ECs on PCBs and disassembly energy. The fifth part, combined with CiteSpace software, discusses in detail the characteristics and trends of research related to the reusing of ECs from three aspects: manual or semi-automatic disassembly, automatic disassembly, and refinement treatment before and after disassembly.

In the “Big data analytics section” of this article, we mainly used CiteSpace software 6.1.R2. to sort and visualize some of the research literature. The data analyzed were obtained from the Science Citation Index Extension (SCIE) of the Web of Science Core Collection (WoSCC) database, which mainly contains the most influential and important journals in the fields of natural sciences, engineering and technology, with high quality articles and is considered by many scholars as the most influential literature search tool and has good adaptability to CiteSpace software. According to the search rules and literature review, the input search terms are set as: TS = (waste printed circuit board) AND TS = (recycling OR recovery OR reuse). A total of 1788 relevant papers were used in this analysis, excluding review and conference proceedings papers. To ensure data integrity, there is no option to crop the database when using the CiteSpace software. The year set within the software starts from 1991, when the search terms first appear in the database, and ends in June 2022. The “selection criteria” were selected in g-index mode.

In the picture made using CiteSpace software, nodes containing purple circles indicate that the “mediated centrality” of that node is to be ≥ 0.10. Mediated centrality is a concept mainly proposed by Freeman,[60] which is a graph-theoretical property that quantifies the importance of a node's position in the network. In CiteSpace software, a node can be considered more critical than other nodes if its centrality ≥ 0.1 (ref. 55). In addition, it is clear that the data analysis from the CiteSpace software only shows the status of the study, not the real situation.

3 Recycling system of WPCBs in various regions

The main purpose of this section is to analyze the regional distribution of recycling of WPCBs using big data visualization and to understand the regions that have contributed more to the recycling of WPCBs and the connection between them. Fig. 2 was made by using CiteSpace software 6.1.R2., selecting the “Countries” button and selecting the year slice as 1. The analysis shows that a total of 74 countries/regions have participated in the study of recovery of WPCBs over the past 30 years, and China and India are far ahead of other countries in the world in terms of the number of publications. In terms of the magnitude of “mediary centrality”, the importance of the research content of each region within the domain of recovery of WPCBs was ranked as India > China > UK > USA ≈ Italy > Japan > Australia > Korea(Table 1). There is a wide disparity in the number of studies in each region. However, this method of analysis is simplistic in judging the importance of each region's research only in terms of “mediary centrality”, so it is not representative of its value in terms of practical industrial applications.

From 1991 to 2022 (June), the People's Republic of China (main-land) has published 546 papers in the direction of recycling and treatment of WPCBs, accounting for 30.54% of all related literature. In the past few years, a large amount of e-waste has been illegally transported from developed countries

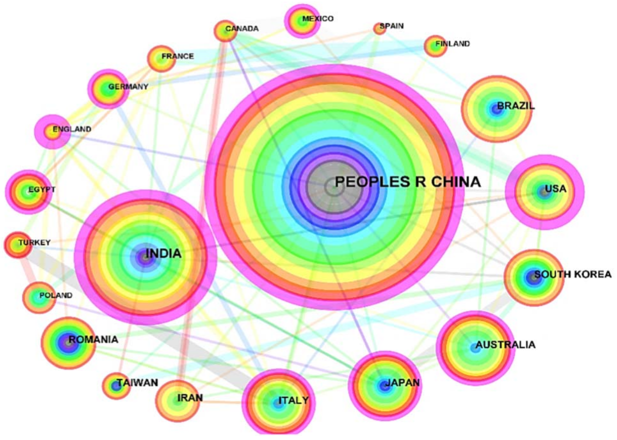


Fig. 2 Visual analysis of the national network of WPCB recycling treatment studies.

Table 1 TOP 15 regions in research on recycling of WPCBs from 1991 to 2022

Count	Centrality	Year	Regions	Proportion (%)
546	0.21	2004	Peoples R China (main-land)	30.54%
152	0.24	2008	India	8.50%
75	0.20	1993	USA	4.19%
75	0.05	2002	Brazil	4.19%
73	0.09	2002	South Korea	4.08%
68	0.10	2010	Australia	3.80%
60	0.15	2004	Japan	3.36%
58	0.20	2007	Italy	3.24%
44	0.02	2008	Iran	2.46%
41	0.06	2009	Romania	2.29%
38	0.07	2000	Taiwan and China	2.13%
33	0.03	1999	Poland	1.85%
31	0.03	2006	Turkey	1.73%
30	0.23	2004	England	1.68%

to the Chinese coast.[61] Therefore, China has more experience in recycling and disposal of e-waste. The process of handling and recycling WPCBs has caused serious negative impacts on the environment and human health in China, and has become a hot issue that needs to be addressed urgently in China. As a major producer and recycler of WPCBs, China has enacted many laws, regulations and national policies in recent years to regulate the recycling industry of WPCBs and to reduce pollution during the recycling process.[62] As shown in Table 2, since 2004, a large number of related laws and regulations have been published in China. The China Materials Recycling Association pointed out that since the fund subsidy system was officially implemented in 2012, China has become one of the countries with the largest volume of formal WEEE disposal in the world.[63] In October 2021, the State Council of the People's Republic of China issued the "Action Plan for Carbon Peaking by 2030″, emphasizing the vigorous development of a circular economy and comprehensive improvement of resource utilization efficiency, and giving full play to the synergy of reducing resource consumption and carbon reduction. As a key component of various EEEs, WPCBs have a high value of reuse and carbon emission reduction.

Before the introduction of relevant policies, the separation of ECs from WPCBs in China relied mainly on manual labor. Workers disassemble WPCBs using a coal furnace without any protective measures. After melting the solder between the ECs and the board in a molten tin furnace, the large components are dragged off directly using pliers or other tools, and then the remaining components are removed by tapping on the back of the board. In 2004, China Central Television (CCTV) reported news of open-air dismantling, dumping and burning of used electronics in Guiyu Town, Guangdong Province, which drew the attention of the government and the public. Investigators from the Basel Action Network (BAN) found that the lead levels in Guiyu Town's river water samples were 2400 times higher than the World Health Organization's drinking water guidelines, and sediment samples contained 212 times more lead

Table 2 The laws and regulations formulated by China in recent years for the recycling of WPCBs

Year	Department	Laws or regulations	Details
2004	The State Council of the People's Republic of China	The measures for the administration of hazardous waste operation permits	Prohibits WPCB comprehensive utilization operation activities without an operation permit or in violation of the provisions of the operation permit
2009	The State Council of the People's Republic of China	Regulations on the management of WEEE recycling	Regulates the disassembly and disposal activities of WPCBs
2012	The Chinese Ministry of Finance and the Ministry of Environmental Protection and other departments	Management measures for the collection and use of the WEEE disposal fund	The state levies WEEE disposal fees from manufacturers for WEEE disposal and a fund is established to subsidize formal recycling and processing enterprises
2017	The General Office of the State Council of China	The general office of the state council of China	Encourages manufacturers to use after-sales service networks to cooperate with qualified dismantling and remanufacturing enterprises to establish a reverse recycling system
2019	Ministry of Environmental Protection	WEEE disassembly and processing situation audit work guide (revision)	Prompted the appliance circuit board disassembly industry to continue to develop in the direction of standardization, efficiency and environmental protection
2021	National Standardization Technical Committee	The requirements for treatment and disposal of waste circuit boards (20210911-T-469) (drawing up)	Requirements for treatment and disposal of WPCBs, requirements for environmental protection and requirements for safety risk containment

than what is considered hazardous waste.[64] Incomplete open burning of electronic waste and dumping of process materials are major sources of various toxic chemicals.[65] A primitive process in the disassembly process of WPCBs means low efficiency, pollution, and inevitable damage to components, which is not conducive to the subsequent reuse of components.[66] In response to the adverse effects of manual dismantling of electronic waste on the environment and human body, China banned the practice in 2011. However, there are still some problems with the actual implementation. First of all, the current policy of WPCBs in China is mostly based on the extended producer responsibility system, which emphasizes the responsibility of producers for the recycling of WPCBs, while consumers are not responsible for the recycling of electronic products, and can even obtain certain benefits through the recycling of WPCBs. This leads to most of the WPCBs in China still being recycled through street vendors or individual recycling enterprises, and their subsequent flow has uncontrollable risks. Second, the relatively small number of formal recycling enterprises has difficulty coping with the increasing annual production of WPCBs. And third, the lack of a dedicated administrative agency to fully monitor and enforce the enacted laws has led to inaction on the part of relevant stakeholders. Finally, the amount of WEEE collected and processed by the formal sector each year has not been mentioned in the legislation. And the lack of information transparency can make it difficult to implement subsequent related efforts.[8,67]

India ranked second in the number of articles with 152. In 2011, the Indian Ministry of Environment and Forests issued the "E-waste Management and Disposal Rules, 2011″. The regulation aims to regulate the Indian market for the collection, storage, transportation, import, export, environmental recycling, treatment and other acts of e-waste. In 2016, the Indian central government issued the "E-waste Management Regulations", which state that the Indian electronic product manufacturers have the obligation to recycle e-waste, and should individually or jointly establish e-waste recycling centers or systems. However, the effect of the regulations was minimal, and even in the following year amendments were proposed to reduce the percentage of e-waste that manufacturers would need to recycle and safely dispose of from 30% to 10%. Although India's Central Pollution Control Board (CPCB) has registered 178 official e-waste recycling or dismantling units, only 27 units in the entire formal sector have the capacity to process more than 5000 metric tons of e-waste per year.[68] In reality, the recycling industry of PCBs in India is still dominated by private workshops, which even contain a large number of child laborers, and there is a growing problem of environmental pollution and health damage due to illegal recycling of electronic components. However, due to the large number of jobs it provides, the Indian government is not able to make a radical change in a short time.

Although the number of publications on WPCB recycling in the U.S. only accounts for 4.19% of all, the "mediary centrality" of related research in the U.S. is as high as 0.20. It can be seen that the U.S. has a strong leadership in research on WPCB recycling. In 2009, the U.S. Environmental Protection Agency (EPA) and the electronics recycling industry jointly developed an industry standard for electronic recycling, known as Responsible Recycling Certification, which is the highest standard in the recycling industry.

As a former EU member, the UK has only 30 publications but a "mediary centrality" of 0.23, higher than both China, which has published more than 500 studies, and India, which has more than 150. Italy has only 58 publications but has a "mediary centrality" of 0.20. EU countries account for 1/3 of the top 15 regions in terms of the number of studies related to the recovery of WPCBs. It can be seen that the EU has done a lot to contribute to WEEE recycling. In the early 21st century, the European Union began to implement uniform laws and regulations for the recycling of electronic waste, such as the Waste Electrical and Electronic Equipment Directive (WEEE Directive), the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Directive (RoHS Directive), the Eco-design Framework for Energy-using Products Directive (EUP Directive), the Waste Electrical and Electronic Equipment Directive (new WEEE Directive), and the WEEELABEX standard (WEEE Label of Excellence). With the support of these laws and regulations, the European Union has established a system of recycling with the responsibility of consumers, sellers and producers. In the WEEE Directive (Fig. 3), ECs on WPCBs are first disassembled and separated in a step, and then classified by means of a certain classification according to their function, integrity or other characteristics, and the components that can continue to be used continue to enter consumer circulation through remanufacturing. In the WEEELABEX standard, it is stipulated that circuit boards over 10 cm^2 need to be separated from WEEE.[63] In 2013, the European Commission (EC) developed the Product Environmental Footprint (PEF) and Organizational Environmental Footprint (OEF) methodologies,[69] establishing a unified green product evaluation criteria, audit and labelling system. The "PEF" is a comprehensive resource and environmental indicator based on life cycle assessment: a method to quantitatively assess the environmental impact of a product or process,[70] which requires an integrated consideration of the environmental impact of material, energy and waste flows throughout the life cycle of a product. The establishment of a unified evaluation tool at the recycling stage will help the

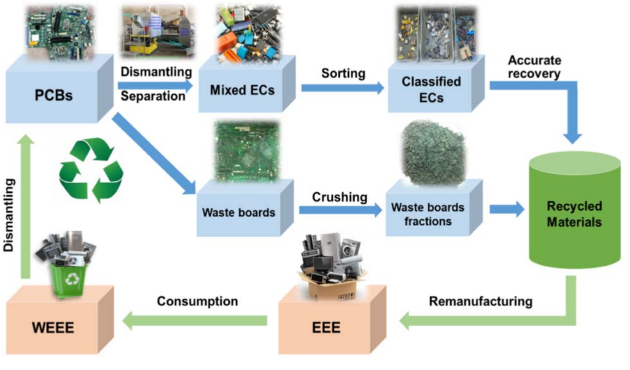


Fig. 3 Recycling flow chart of a PCB in WEEE.[71]

PCB recycling industry develop in the direction of standardization, greening and efficiency. At the end of 2014, the EU approved the first WEEE treatment standard "Collection, logistics & treatment requirements for WEEE-Part 1: general treatment requirements " (EN 50625–1). The standard specifies that "the mass of WEEE prepared for re-use" is used to calculate the recycling rate and that treatment of WEEE should "avoid damage where there is the potential for preparation for re-use".[43]

The number of articles issued in Japan and Korea is not high, about 10% of the first place, but both of them have a "mediary centrality" of about 0.1. In 2007, the Korean government introduced "the Electrical and Electronic Products and Automotive Resources Recycling Act", which is a life-cycle management system for electrical and electronic products and automobiles. Under the extended production responsibility (EPR) system, Korean manufacturers are responsible for the recycling of their products, while the local government or municipalities are responsible for the recycling of electronic waste discarded by residents, with the residents and the government sharing the costs.[67] Japan has also enacted a series of laws and regulations in recent years to promote the recycling of electronic products, such as the Law for the Promotion of Effective Use of Resources, the Law for the Recycling of Home Appliances, and the Law for the Recycling of Small Electrical and Electronic Products. According to the relevant laws, consumers are responsible for the cost of transportation and disposal of electronic waste in Japan. In addition, Japan has adopted heavy penalties in law to prevent illegal disposal of electronic waste.

Although there is more research on circuit board recycling in developing countries such as China and Indonesia, there is still a gap between it and practical industrial applications. In general, China has an advantage over India in terms of the scope and enforcement of laws and regulations, management systems and technology, but both countries need to make further changes compared to the recycling systems of developed countries.[72] First, although reuse is common in the recycling process and most countries have measures in their waste management laws or regulations to promote reuse, the implementation varies from country to country. The EU[73] clearly states that "where appropriate, priority should be given to preparing for the reuse of WEEE and its components, assemblies and consumables". However, the WEEE Recycling Management Regulation, which is commonly considered China's WEEE Directive, does not consider the issue of reuse. Reuse is rarely addressed in the current official Chinese guidelines and standards.[43] Second, according to the "National Hazardous Waste List (2021 Edition)" issued by the Ministry of Ecology and Environment of China, waste circuit boards (including waste circuit boards with or without dismantled components), and waste CPUs, graphics cards, sound cards, memory, capacitors containing electrolyte, and connections containing gold and other precious metals generated during the disassembly of waste circuit boards are hazardous waste (HW49, 900-045-49). Its disposal should comply with the requirements of the measures. However, according to the U.S. "Resource Conservation and Recovery Act" (RCRA), shredded circuit boards can continue trading activities without being disposed of as hazardous waste. Japan, Canada and Australia do not have special instructions on whether WPCBs are hazardous waste. Compared with these developed countries, China classifies components on waste circuit boards as hazardous waste, resulting in components that could be sold now needing to be given to hazardous waste treatment enterprises. However, there are currently few technology companies in the Chinese market that can handle and dispose of the components generated by dismantling used circuit boards. This not only causes a waste of resources, making the waste circuit board in the terminal disposal of the environment has brought a certain burden, but also makes the disposal of enterprises and appliance dismantling enterprises an increased burden.[63] Third, the recycling treatment of electronic products such as WPCBs in developed countries is usually shared by consumers, producers and the government. However, in China and India, consumers do not seem to be responsible for recycling and can even profit from it. As well, although there is an EPR system, the producers of electronic products are not responsible for the recycling and disposal of their products, which is not conducive to the construction of a WEEE recycling and resource utilization system, and even less beneficial to the realization of the global low-carbon concept. Finally, e-waste recycling in many developing countries is mainly operated by the informal sector and is not well modernized:[74] First, most developing countries lack technical standards for the recycling of WPCBs. Second, the disassembly process of WPCBs used in these countries is not highly automated, leading to its high dependence on manual labor; environmental protection is not high, and it is easy to produce secondary pollution in the component recycling process; the desoldering process is inefficient and damaging, and the classification of components after disassembly is insufficient, which is not conducive to the reuse of a series of high-value components such as circuit board surface chips, CPUs and GPUs. Developed countries such as Japan and Germany have developed methods for automatic component disassembly, fine sorting and recycling. However, due to its larger scale, more complex process and higher economic costs, it has not been transferred to developing countries such as China and India. In addition, from the perspective of participating companies, the United States has more than 2000 qualified companies, while China has only 109 and the EU has more than 500. Therefore, there is an urgent need to develop sustainable dismantling technologies for WPCBs in developing countries in Asia and Africa.[52]

4 Theoretical basis for reuse of ECs from WPCBs

As the first and critical step in the pre-processing of WPCBs, disassembly of ECs is one of the most difficult tasks in the reuse of used electronics,[75] and has a significant impact on the process of recycling WPCBs.[76,77] Some researchers[54] have shown that the depletion of the disassembly process of ECs has a negligible impact on the economic profit obtained from the reuse process of ECs. In the disassembly process of ECs, there are two crucial aspects. The first is the release of the solder, that is, through various methods to melt the solder between the components and the PCB and release the connection force. The second step is disassembly, mainly through external forces to separate the substrate and has been released from the connection of components.[78] The dismantled ECs are identified and classified according to their high value and toxicity, and the high-value components are recycled and reused in the consumption process, while the other low-value components are recycled or harmlessly treated according to their toxicity.

4.1 Desoldering

Desoldering is the first and critical step in reusing ECs on WPCBs. Desoldering mainly includes grinding off the solder joints on the back of a PCB with a grinder; dissolving the solder with chemical reagents; melting the solder by different heating methods such as using infrared heaters, electronic heating tubes, hot air and hot liquids. As a connection between bare boards and ECs, different types of solders have varied properties. The solder used in the traditional soldering process is mostly tin-lead solder; the most commonly used is the ^{63}Sn/^{37}Pb eutectic alloy, which has a low melting point (183 °C), good wettability, high conductivity and low cost.[79] However, due to the harmful nature of Pb, the EU introduced the "Restriction of Hazardous Substances Directive" (ROHs) in 2006, which stipulates that leaded solder can no longer be used in electronic products.[80,81] Therefore, in recent years, Sn-based solders have replaced traditional Sn–Pb solders to a certain extent.[82] Current lead-free solders can be divided into binary solders, ternary solders and miscellaneous additions.[83] Among them, the Sn–Ag–Cu alloy is considered to be the most beneficial and promising lead-free brazing material,[84–86] with a melting point between 217 °C and 225 °C.[87–89] The melting point and other properties of the solder are closely related to the temperature required for desoldering. Several researchers[90–92] have shown that at temperatures above the melting point of Sn–Ag–Cu solder, the cohesion between ECs and PCBs is weakened, leading to a rapid increase in desoldering efficiency. However, after 250 °C, the melting rate of the solder does not increase with the increase in temperature. And at around 280 °C, toxic gases are also generated. In addition, some ECs consist of adhesive and solder soldered together on the substrate.[93] Therefore, when disassembling this type of EC, it is important to pay attention to not only the nature of the solder, but also to analyze the nature of the adhesive to determine the appropriate desoldering process, so that resources can be saved and the environmental impact can be reduced during the recycling process.

Researchers[66] from Shanghai Jiao Tong University evaluated various desoldering methods and stated the limitations of various methods for industrial applications (Table 3). Researchers at Nanyang Technological University[59] have qualitatively compared various approaches in terms of operating expenses (OPEX) and capital costs (CAPEX). From an environmental impact point of view, the stripping of solder, whether by hot liquid or chemical methods, generates a certain amount of pollution, while surface grinding, hot air heating, hydrothermal and supercritical fluid methods and high voltage electric pulse crusher treatment are less polluting to the environment. From a production cost perspective, the total cost (OPEX + CAPEX) is lower for surface grinding, crude oil heating, infrared heating and chemically dissolved solder. In addition, researchers from Shanghai Jiao Tong University[66] concluded that most desoldering methods are inefficient and not suitable for industrial applications, while researchers[59] from Nanyang Technological University concluded that hot air, infrared, and hot liquid heating methods have high desoldering efficiency. The writer believes that the two parties considered the issue from different perspectives, the former mainly from the perspective of industrial applications and the latter mainly from the comparison of the efficiency of various methods.

In comparison, the mechanical grinding method and the hot air heating method are the most suitable methods in terms of environmental impact, efficiency and cost. However, both of these methods have some problems. Mechanical grinding is more suitable for processing WPCBs one by one, and it is difficult to use uniform grinding lines due to the different structures of various WPCBs, resulting in a lower industrial applicability of the method. Although the hot air heating method of melting solder can process large quantities of WPCBs at the same time, this method also has some limitations. As mentioned earlier, WPCBs are highly heterogeneous and complex.[94] Differences in heat capacity and inhomogeneous distribution between components can lead to an inconsistent temperature increase in different regions of WPCBs during heating, which can result in the destruction of ECs during desoldering. And the components on the WPCBs will absorb moisture when they are disposed of outside. The heating temperature will cause moisture diffusion and expansion inside the chip, resulting in stresses that are greater than the internal interlayer bonding force, causing delamination defects in the chip.[95] It can be seen that different methods have different advantages and disadvantages, and choosing the appropriate desoldering method according to different board types is the first and crucial step to reuse ECs on WPCBs.

4.2 Disassembly

The disassembly process includes mechanical (gripping, vacuum suction, vibration and impact) stripping, gas jet stripping and the use of gravity, centrifugal force, shear force, *etc.*[59,66,78,96] As shown in Table 4, most of the methods have certain drawbacks leading to their industrial inefficiency. Some researchers[97] conducted a series of simulations of the WPCB disassembly process using a combination of the genetic algorithm (GA) and discrete element method (DEM) to evaluate the effects of various disassembly techniques on the nondestructive peeling of ICs. The simulations found that although the water jet method, which is not destructive to IC chips, does not completely achieve the separation of ICs from the substrate, the

Table 3 Characterization of removal methods for solder joints[66]

Damage method for solder joints	Advantages	Limits for industrialization	Potential for industrialization
Physical grind	No need for heating (less secondary pollutants)	1. WPCBs must be fixed 2. Strict requirements for the position of WPCBs	Low due to low efficiency
Chemical reagents	No need for heating	1. Large amounts of secondary pollutants generated (wastewater, waste gas, *etc.*) 2. Difficulty of selection of suitable chemical reagents (dissolve solder only) 3. The dismantled ECs and WPWBs need to be further cleaned	Low
Infrared heater	Clean reagent High heating speed	1. High economic cost 2. Damage to the other materials of WPCBs rather than solder only due to the high heating speed, penetrating heating, and differences in the absorption rate	Not suitable for less developed countries
Hot liquid (diesel, paraffinic oil, silicon oil, *etc.*)	Large thermal capacity Even temperature field relatively High heating speed relatively	1. Difficulty in disposing of used hot liquid 2. The dismantled ECs and WPWBs need to be further cleaned 3. Hard to realize automatic feeding and automatic discharging	Low
Molten solder	Large thermal capacity Even temperature field High heating speed	1. Low efficiency for hard to realize automatic feeding and automatic discharging 2. Workers must be exposed to a high temperature liquid solder bath 3. Hazardous to the environment and to workers due to solder vapor generated	Low

Table 4 Characterization of external forces for disassembling from WPCBs[66]

External force	Limits for industrialization	Potential for industrialization
Mechanical sweep	1. WPCBs must be fixed (most of them are manual at present) 2. Strict requirements for the position and the layer number stacked up WPCBs	Low due to low efficiency
Gas jet	1. WPCBs must be fixed (most of them are manual at present) 2.Strict requirements for the position and the layer number stacked up WPCBs	Low due to low efficiency
Centrifugal force	1. The back of WPCBs (the side without ECs) must be toward the inner surface of the cylinder 2. Only one-layer WPCBs could be placed along the inner surface of the cylinder	Low due to low efficiency

mechanical impact method is used to dislodge the ECs by deforming the substrate.

The board of WPCBs mainly supports and connects the components on the surface in series, while the ECs on top of the board form the structure of the circuit.[98] According to the "Printed Circuits Handbook", ECs are generally fixed to the substrate through four types of welding,[15] but currently the more popular are the SMD assembly technology (SMT) and jack assembly technology (THT) (Fig. 4). SMT was developed in Europe and is one of the most popular technologies and techniques in the electronic assembly industry today. It is a circuit assembly technology in which surface-mounted components (SMC/SMD) without pins or short leads are mounted on the surface of a PCB or other substrates by reflow or dip soldering. THT is a technique for establishing long-term mechanical and electrical connections by inserting leads on a component into a through-hole reserved on the PCB and then soldering them to the other side of the substrate. SMT does not need to reserve the corresponding penetration holes for the pins of the components, and the size of the components is also much tinier than that of THT technology. Small components such as chips are generally soldered using SMT, while large components are usually soldered on bare boards using THT.

A study by the NEC Corporation of Japan[93] found that the use of a vertical force was more effective than the use of a horizontal force when removing through hole devices (THDs), while a horizontal force was more effective when removing surface-mounted devices (SMDs). Researchers[75] at Tsinghua University have also demonstrated that disassembly of THDs and SMDs from PCBs requires different disassembly methods. After the

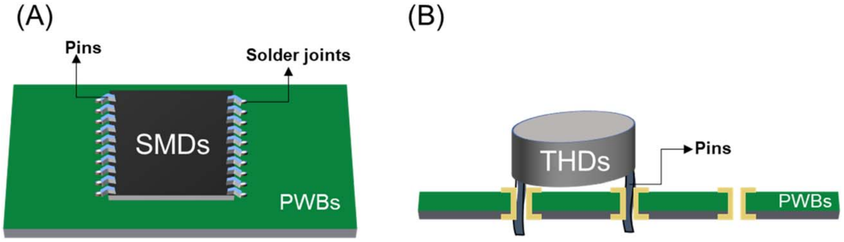


Fig. 4 Two fixation methods for printed circuit boards (PCBs): (A) SMT and (B) THT.

solder is melted, if the pins of a THD are not bent, they can be disassembled with a small force or acceleration, and even the THD can come off by itself without external force, but in the case of bent THD pins, the required removal force is larger and increases with an increase in the pin bending angle. In addition, Xiang *et al.*,[95] found that a few ECs could not be disassembled by providing only a large enough disassembly force due to the large mounting base area. Therefore, based on the quantitative study of the disassembly force, the concept of separation displacement was proposed: the factors that determine the successful disassembly of a component should include the disassembly force and the separation displacement of the solder, which is the disassembly energy. Under the conditions of solder melting, in order to successfully disassemble the components from the board, it is necessary to provide energy higher than the minimum disassembly energy. Subsequently, Xiang *et al.*[99] established a vertical vibration disassembly model for WPCBs based on the disassembly energy study, and the effective disassembly energy diagram proposed by the team can not only discern whether different components on WPCBs can be disassembled and separated at the set excitation frequency, but also predict the required excitation frequency for component disassembly and separation.

In summary, the disassembly process should be selected in a way that allows for the efficient disassembly of components in different mounting forms. And it is necessary to provide the minimum disassembly energy required for component disassembly, while minimizing the energy consumption of the disassembly process and reducing the environmental risks of the disassembly process.[95]

5 Current status and development trends of EC reuse research

Fig. 5 shows the "keyword" graph obtained using CiteSpace with the "keyword" button selected and a year slice of 1. The figure shows the research hotspots related to the recycling of WPCBs between 1991 and June 2022. Among the literature analyzed,

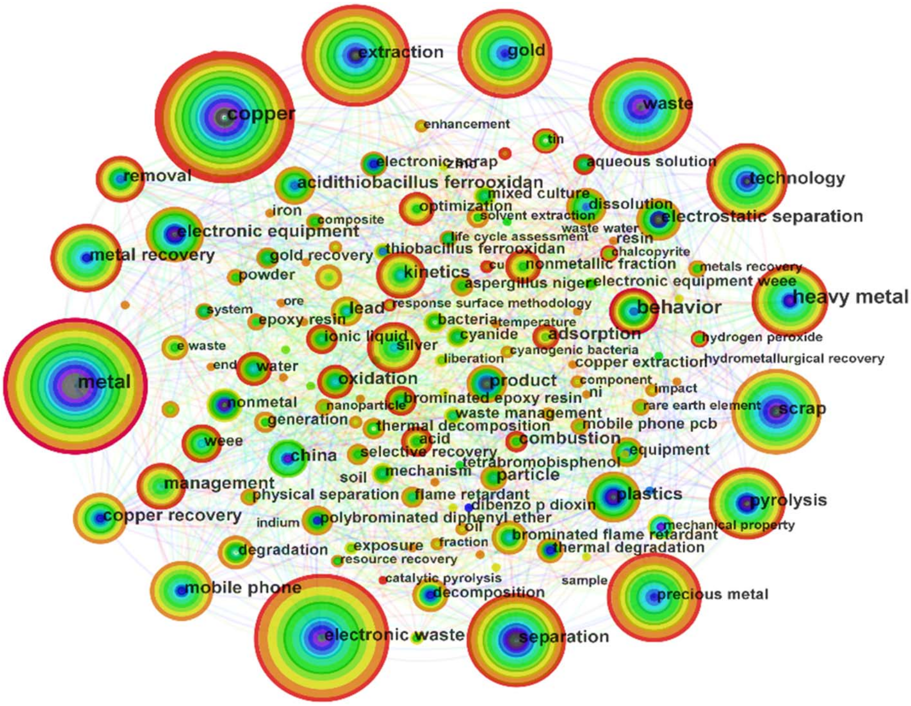


Fig. 5 Keyword analysis in the field of WPCB recycling from 1991 to 2022.

a total of 318 papers are related to "metal", 317 papers are related to "copper", and 191 papers are related to "gold". Within the top fifteen keywords in terms of quantity, half of them were related to metals, except for five terms which were related to WPCBs. It can be seen that past studies often focus on the recycling of raw materials, especially regarding the recycling of metallic materials,[100–109] but not much research has been conducted on the separate recycling of ECs.

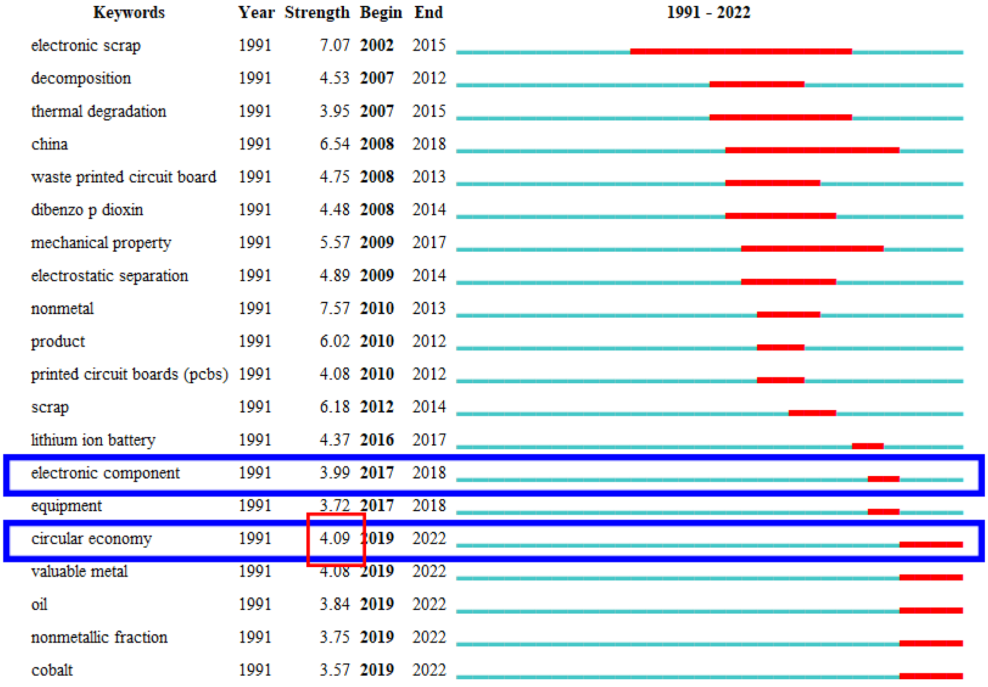
Fig. 6 shows the "keywords with the strongest Citation bursts" diagram obtained by using CiteSpace and selecting the "keyword" button and slicing the year to 1. For clarity of data, "printed circuit boards" and its related "wpcb", "waste printed circuit boards" and "waste pcb" are hidden. Fig. 6 describes the development trend of research related to recycling of WPCBs as a whole. It can be seen that the focus of research gradually shifts from traditional recycling methods and various raw materials to fine recycling, high-tech applications, resource utilization and environmental impact, and the attention paid to ECs on circuit boards is also gradually increasing. Some researchers[110] have also indicated that the focus of research on WPCBs will shift from technology development to large-scale industrial applications.

On the basis of the theory about disassembly, more efficient and less damaging disassembly methods imply higher reuse rates and higher economic efficiency. Therefore, effective disassembly of ECs can significantly improve the efficiency and scale of the circuit board recycling industry[111] and can be effective in saving scarce resources and eliminating potential hazardous substance exposure to maximize economic returns and minimize environmental pollution.[53] The current global EC disassembly process is mainly divided into automatic disassembly and non-automatic disassembly. The main difference is whether there is manual involvement. The various disassembly methods are summarized in Fig. 7 and described in detail below.

5.1 Manual or semi-automatic disassembly

Compared with automatic disassembly equipment, non-automatic disassembly equipment requires more manual involvement and is less efficient, which has little advantage in industrial applications. However, automatic dismantling equipment is developed from non-automatic dismantling equipment which has certain guiding significance for the research of automatic dismantling equipment.

Some researchers have chosen to utilize wet methods to remove ECs from PCBs. The researchers[112] used fluoroboric acid (2.5 mol L^{-1}) containing 0.4 mol L^{-1} oxidant H_2O_2 to selectively dissolve the solder within 35 min. Due to the addition of the oxidant, the ECs could be easily removed from the board and good external characteristics could be maintained. On this basis, this team[113] also used a combination of methanesulfonic acid (MSA) solution and H_2O_2 to dissolve the solder on WPCBs. Using 3.5 mol L^{-1} MSA with 0.5 mol L^{-1} H_2O_2, the leaching rate of tin-lead was nearly 100% and the total dissolution rate of copper was less than 5% at a reaction time of 45 min. By the grey relational analysis and Taguchi technique, Soni *et al.*[114] found that best results were obtained by using 2.5 moL l^{-1} HBF_4, 0.40 moL l^{-1} H_2O_2 and 3.0% HNO_3 to treat the solder. After 40 minutes of reaction, the solder was completely dissolved and the ECs could be easily detached without any adverse effect on the color, symbols and characters on the surface of the PCB. Pinho *et al.*[115] used an alkaline solution of 1 mol L^{-1} NaOH to



Keywords	Year	Strength	Begin	End
electronic scrap	1991	7.07	**2002**	2015
decomposition	1991	4.53	**2007**	2012
thermal degradation	1991	3.95	**2007**	2015
china	1991	6.54	**2008**	2018
waste printed circuit board	1991	4.75	**2008**	2013
dibenzo p dioxin	1991	4.48	**2008**	2014
mechanical property	1991	5.57	**2009**	2017
electrostatic separation	1991	4.89	**2009**	2014
nonmetal	1991	7.57	**2010**	2013
product	1991	6.02	**2010**	2012
printed circuit boards (pcbs)	1991	4.08	**2010**	2012
scrap	1991	6.18	**2012**	2014
lithium ion battery	1991	4.37	**2016**	2017
electronic component	1991	3.99	**2017**	2018
equipment	1991	3.72	**2017**	2018
circular economy	1991	4.09	**2019**	2022
valuable metal	1991	4.08	**2019**	2022
oil	1991	3.84	**2019**	2022
nonmetallic fraction	1991	3.75	**2019**	2022
cobalt	1991	3.57	**2019**	2022

Fig. 6 Keywords with the strongest citation bursts in the study of recycled WPCBs from 1991 to 2022.

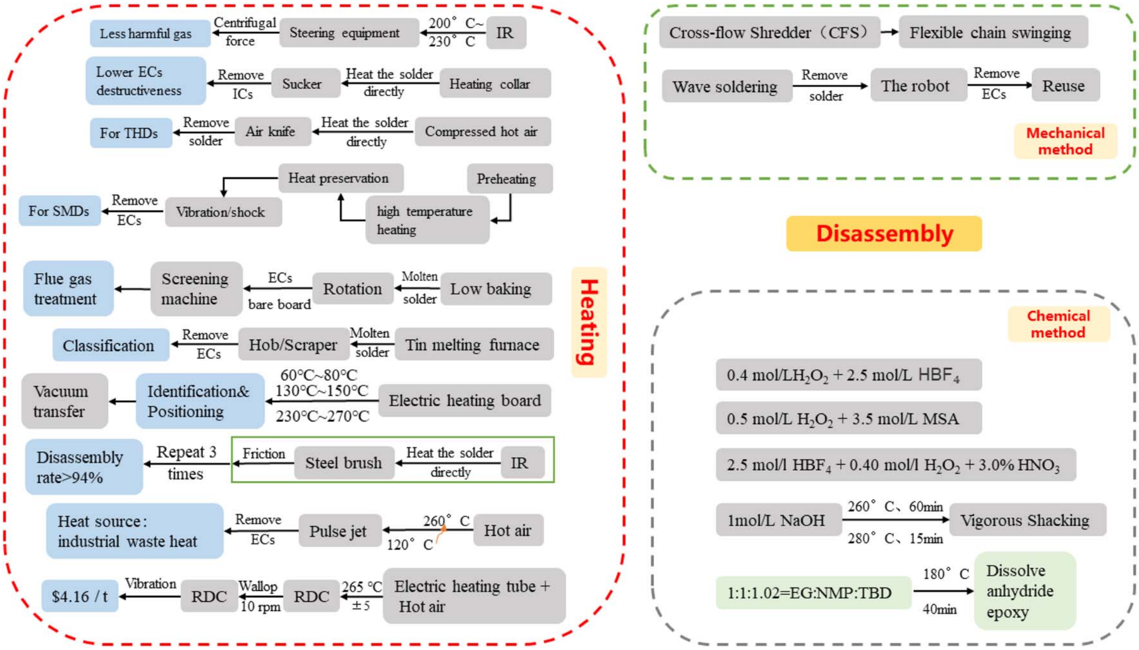


Fig. 7 Classification of the disassembly process of ECs on WPCBs.

dissolve the solder, and then separated the ECs from the substrate by vigorous shaking after the solder was dissolved. The ECs can be easily separated from the substrate at 260 °C for 60 minutes or 280 °C for 15 minutes. However, this method is very destructive to ECs such as chips and inductors and is not conducive to recycling of components. Overall, the problem with the wet process is, on the one hand, that the usage of chemical reagents is relatively large and the pollution to the environment is relatively heavy. On the other hand, the function of the electronic components of ECs recovered by the wet process is inevitably damaged to a certain extent during the treatment process, which affects the subsequent reuse. In this regard, researchers at Xi'an Jiaotong University[116] proposed a dynamic reaction-based small molecule-assisted method for the recovery of ECs from WPCBs. The main principle is to use the hydroxyl group in the ethylene glycol (EG) solvent to exchange with the ester bond in the epoxy network of the substrate. The method differs from other methods in that it does not remove ECs by desoldering, but rather by a novel method of dissolving the bare board to recover ECs. And the advantage of this method is that the treatment process is environmentally friendly and efficient.

The mechanical method is more economical and has a lower environmental impact than chemical stripping of solder. The cross-flow shredder (CFS) developed by Satotekk, Japan, is a drum-type agitator mill using a chain that allows non-destructive stripping of ECs. It has been used in recycling of WPCBs because its flexible chain can reduce excessive damage to ECs during disassembly.[117] Ueda *et al.*[97] found that a CFS mainly deforms the substrate using mechanical force to disassemble ECs. In particular, by designing experiments, the researchers[118] found that adding screens to the sidewalls and bottom of a CFS would reduce the possibility of over-crushing the samples and improve the reusability of the ECs.

Compared to mechanical disassembly alone, increasing the temperature of the treatment process by various methods will significantly improve the removal efficiency of ECs. Liyang Extra Strong Chains Mfg Co Ltd[119] designed non-destructive disassembly equipment for WPCBs, mainly using infrared heating tubes to fully melt the solder and then using a steering device with a swing arm to use centrifugal force to detach the components on both sides of the board. The advantage of the device is that the air temperature in the cavity of the rack can be maintained at 200 °C to 230 °C, to avoid the production of a large number of harmful gases. However, the device needs to complete the feeding and discharging operation manually in batches, and cannot be continuously automated. China Sanderson Blue Environmental Technology Co., Ltd[120] has developed a non-destructive chip disassembly device. The device mainly removes the tin wire around the chip by heating a molten tin sleeve ring with a temperature controller and then sucks up the disassembled chip with a suction cup. This method directly heats the solder joint itself, which minimizes disassembly energy consumption and effectively reduces damage to the component caused by the thermal disassembly process, thus effectively ensuring the reusability of the disassembled component. But this device requires manual participation throughout the operation process, and the degree of automation is not high, which is not conducive to the promotion of large-scale mechanization. Based on a study of PCB disassembly forces, Xiang *et al.*[95] proposed different disassembly methods for SMDs and THDs. WPCBs with THDs are mainly dismantled by using air knives to form compressed hot air for solder removal and collection. For WPCBs with SMDs, the three-stage heating method of preheating, high-temperature heating and holding is mainly used. This method solves the problem of delamination defects of IC chips during the heating process. After melting the solder, a combination of vibration/impact disassembly and horizontal scraping disassembly is used. These two methods use different disassembly processes according to the different soldering methods of ECs, both of which can effectively reduce the energy consumption of the disassembly process.

5.2 Automatic disassembly

Compared to manual disassembly or semi-automatic disassembly, automated disassembly processes offer great advantages in terms of engineering applications and labor savings. However, so far, the application of automation and robotics in dismantling ECs from WPCBs is still mainly focused on assembly, and only some pilot or demonstration projects will use automated disassembly processes for ECs, and they are mainly realized in research institutions.[76]

Because heat increases the efficiency of solder removal and enables simultaneous desoldering of a large number of samples, most automated disassembly processes utilize a variety of methods to increase the temperature of the disassembly process. The disassembly equipment developed by the China Energy Conservation Engineering Research Institute[121] mainly uses a baking machine to bake WPCBs at low temperatures. During the baking process, the ECs are gradually separated from the boards and the bare boards are separated by the rotation of a metal grid, which is then coarsely screened in the lower part of the oven or sieved using an externally connected sifter. The fumes generated during the baking process are discharged through the second combustion chamber and the fume treatment equipment after reaching the standard. The device in the disassembly process uses the oven directly for baking the entire board, which, due to the nature of the difference between the bare board and electronic components, may cause different degrees of circuit board cracking and damage to the ECs.

The disassembly equipment developed by the Hunan WanRong Technology Company[122] enables the separation of different types, shapes and sizes of ECs. The equipment is mainly used to strip the components by using a combination of a self-controlled electrically heated molten solder furnace, a hob and a squeegee in an assembly line. After melting the solder in the furnace, the large components are removed manually, and then the front solder is continuously removed through the interaction of the hob and scrapers fixed on the assembly line, while the back solder is continuously removed by friction and vibration between the circuit board and the wire mesh and hob on the conveyor belt. At the same time, different baskets are set up under the line for initial sorting of solder, components of different sizes and bare boards. High temperature, odor and harmful gases generated in this process are adsorbed by means of negative pressure adsorption and discharged after environmental protection treatment. The problem with this equipment is that it requires manual removal of large ECs during the process, which increases the labor input and leads to its lack of automation.

The equipment designed by Shanghai Polytechnic University[123] for non-destructive chip disassembly mainly consists of a heating processing unit and a chip disassembly and sorting unit. In order to avoid the thermal stress from damaging the chips due to the temperature difference, an adjustable electric heating plate is used to achieve a gradual temperature increase. The heating process is set up in 3 stages: 60–80 °C, 130–150 °C and 230–270 °C. After the solder is melted, the exact location of the chip to be removed is identified using a camera and the software of the upper computer, and the individual components are reverse-sucked and sorted for recycling by vacuum suction cups. The advantages of this device are high automation, high yield of disassembled chips, and wide range of disassembled circuit board models, but the disadvantage is that the width of the samples fed into the same batch needs to be consistent, and it is impossible to handle many different shapes and sizes of WPCBs at the same time.

The automatic disassembly device designed by Park *et al.*[92] mainly uses an infrared heater to directly heat the solder joint and then uses a steel brush that rolls faster than the feeder to peel off the ECs that have been detached from the substrate by friction. ECs connected to WPCBs by rivets or screws can also be easily peeled off since the process is repeated three times for WPCBs after the solder is melted. When the equipment is fed at a speed of 0.33 cm s^{-1} and heated at 250 °C, the disassembly rate can reach 94%. However, the device disassembles a single WPCB in up to 70 s, which is not efficient and not suitable for large-scale industrial application.

The device developed by Chen *et al.*[52] mainly used hot air to melt the solder and used pulsed jets to separate the ECs from the WPCBs. Under the condition that the preheating temperature was 120 °C and the heat source temperature was 260 °C, almost all THDs and large SMDs on WPCBs were disassembled after 2 min, but the disassembly rate of small SMDs was only 39.73%. On this basis, the use of hot steam generated from industrial waste heat as a heat source to melt the solder was proposed to provide an efficient, promising and green method for electronic component recycling and industrial waste heat recovery. However, there are problems during the operation of this equipment such as the risk of explosion, the small range of applicable WPCBs, the low disassembly rate of small SMDs, the strict requirements in feeding and the absence of environmental protection measures during the operation of this equipment. Based on this, Wang *et al.*[66] improved the above equipment and developed a new ECs-ADM apparatus. The ECs-ADM apparatus combines electric heating tubes and hot air to melt the solder and replaces the conveyor and pulse jet with a rotating demolition cylinder (RDC) and a vibrating sorter screen (VSS). The WPCBs entering the ECs-ADM are first heated using both hot air and electric heating tubes installed around the RDC and then rotate to a high level with the RDC and fall, and the impact makes some of the ECs fall off. After desoldering, the WPCBs fall to the VSS by gravity, and the VSS separates the ECs, solder and substrate by vibration. When the disassembly temperature is 265 ± 5 °C and the speed is 10 rpm, the

ECs are all disassembled after 8 min. In addition, the exhaust gas from the machine is purified and re-entered into the air heater as a heat source to save energy. The cost of treatment with this equipment was estimated to be about $4.61 per ton of WPCBs, taking into account the depreciation cost of the equipment and the power consumption.

Besides various automatic disassembly devices, some researchers have also started to use artificial intelligence to handle WPCBs. Marconi *et al.*[54] proposed a robotic system for automatic disassembly of ECs with a damage-free rate of 100% for EC disassembly. The system uses wave soldering to remove the solder from WPCBs, and then a suction gripper on a mobile robot arm to pick up the dislodged ECs. Since each part of the robotic system is equipped with sensors and controllers, the disassembly process can be regulated at any time. According to the test, it takes about 137 seconds to process a WPCB, and the disassembled ECs can be reused directly on a new PCB without additional processing. The advantage of this system is that it is fully automated and has a high rate of undamaged dismantling, but the disadvantage is that the processing time is too long and the system is not stable enough.

5.3 Post-disassembly process

In order to reuse ECs after dismantling, we must first classify them according to function and type. China RenXin Technology Co., Ltd[124] has developed an environmentally friendly component sorter that is capable of initial sieving of disassembled components from WPCBs. The sorter sorts the disassembled ECs through a continuous reciprocating motion of the screen. The upper screen screens out components with diameters greater than or equal to 30 mm, the second screen sorts out components with diameters greater than or equal to 15 mm, and smaller ECs fall from the lower end of the second screen. Since this system can only screen ECs according to different particle sizes, it is generally only used for preliminary and rough screening of ECs after disassembly. In addition to the primary screening of ECs using mechanical forces, some researchers have also proposed the use of machine learning and deep learning to classify the recycled components. Katti *et al.*[125] developed a machine vision system that can sort and automatically separate ECs according to their functions. The system successfully separates ECs such as ICs, capacitors, relays, and rectifiers. The cost of the system is low because the system uses a simple webcam and a basic microcontroller for identification and sorting, Naito *et al.*[126] proposed a deep learning based PCB recycling system which performed well in the identification and classification of recycled components. In this system, a mechanical gripper with sensors uses convolutional neural network (CNN) processed images to identify different types of ECs and clip them for separation. The problem with this system is that the recognition accuracy and speed are not enough, and the success rate of clamping using the robot is not high, which is not conducive to large-scale industrial applications.

In addition, whether the EC is still valuable after classification can be tested by certain methods. Debnath *et al.*[12] summarized the different types of ECs on PCBs, providing examples of each group of components and their material composition, along with the criteria and recycling options that must be met to reuse these components (Table 5). Generally speaking, every IC manufactured has to pass a test to determine whether the chip is defective or defect-free.[127] Therefore, the same approach can be used in the process of reusing ICs to test old ICs to determine whether they still have reuse value. In addition, some researchers[39] believe that the traceability of electronic components is also essential to estimate the

Table 5 The composition of different types of electronic components and the conditions that need to be met for reuse[12]

Group of components	Examples of components in each group	Criteria to be satisfied for reusability
Passive components	Resistors, capacitors, inductors, thermistors *etc.*	Test result of resistance/capacitance/inductance within tolerance value
Analog components	Diodes, BJT, and FET	Multimeter testing
Analog, digital and mixed signal Ics	Logic ICs, mux, demux, encoders, decoders, Clock & Timer ICs, ADCs, DACs, NE555 *etc.*	Functioning of pins, proper voltage level, proper timing of the output signal, and an acceptable SNR
Connectors	I/O connectors, IC & components Sockets, terminals, memory connectors *etc.*	Isolation & continuity test
Microprocessors	AMD turion, Inteli7, and HP capricon	Structural testing, and functional testing without fault models and using specific fault models
Microcontrollers	Atmel AT89 series, PIC 18 series *etc.*	Generating test signals and testing MCU outputs (cdn.teledynelecroy.c om)
Circuit protection components	Thermal cutoffs, fuses *etc.*	Proper functioning of the protection mechanism as per requirement
Power management circuits	Batteries, power cords, power inverters *etc.*	Acceptable power output
Memory components	RAM, ROM, and hard-drive	Read, write, speed, and capacity
Application of specific processors		Testing method of a processor, in this case satisfying the needs of the application it is made for
ICs used for specific applications		General IC testing technique

remaining life of used components and to establish a market for used devices. Therefore, a new accurate failure probability density model is proposed that can be used to assess the reliability of systems using reused components.

6 Conclusion and discussion

This paper first discusses the existing WPCB recycling and reuse systems in many regions of the world, and then focuses on the theoretical basis and research progress of the reuse of ECs from WPCBs. The main findings are as follows:

(1) Through CiteSpace analysis, it was found that China and India are far ahead of other countries in the world in terms of the number of publications related to WPCB recycling. In terms of the magnitude of "mediated centrality", the importance of the research content of each region within the domain of recovery of WPCBs was ranked as India > China > UK > USA ≈ Italy > Japan > Australia > Korea. Although there is more research on recycling of WPCBs in developing countries such as China and Indonesia, there is still a gap between it and practical industrial applications.

(2) Although there is a lot of research on the recycling of WPCBs in China, there are many problems in the practical application. First, there is very little content related to e-waste reuse in China's WEEE management system. Secondly, compared to developed countries, China classifies components from WPCBs as hazardous waste, resulting in components that were previously marketable now needing to be handed over to hazardous waste disposal companies. Finally, in China, despite the EPR system, the producers of electronic products are not responsible for the recycling of their products and consumers do not seem to be responsible for recycling and can even make a profit from it.

(3) E-waste recycling in many developing countries is mainly operated by the informal sector. First, most developing countries lack technical standards for recycling of WPCBs. Second, the disassembly process of WPCBs used in these countries is not highly automated, leading to its high dependence on manual labor; environmental protection is not high; it is easy to produce secondary pollution in the process of component recycling; the desoldering process is inefficient and damaging; insufficient classification of components after disassembly. Developed countries such as Japan and Germany have developed automatic component disassembly, and fine classification and recycling methods; however, they have not been transferred to developing countries such as China and India due to their larger scale, more complex processes and higher economic costs. Therefore, there is an urgent need to develop sustainable disassembly technologies for WPCBs in developing countries in Asia and Africa.

(4) ECs still have high use value when WPCBs are scrapped, so the bare board and electronic components should be separated in advance in the pre-processing stage; otherwise in the processing stage, contamination from multiple metals and plastics mixed with each other will increase the difficulty of recycling and increase the environmental impact of processing.

(5) During the disassembly work of ECs on WPCBs, there are two key aspects. The first is desoldering, *i.e.*, melting the solder between the components and the PCB by various methods and releasing the connection force therein. The second link is disassembly, mainly by external force to separate the substrate from the components that have been unconnected. In comparison, in the desoldering process, the mechanical grinding method and the hot air heating method are the most suitable methods in terms of environmental impact, efficiency and cost. In addition, it is essential to use different disassembly means for SMDs and THTs on WPCBs. Finally, while ensuring the provision of the minimum disassembly energy required for component disassembly, the energy consumption of the disassembly process should be minimized and the environmental hazards generated by the disassembly process should be reduced.

(6) At present, the whole process of disassembly of ECs worldwide is mainly divided into automatic and non-automatic disassembly, and the main difference is whether there is manual participation or not. The disassembly process is mostly a combination of the heating process and mechanical process, but all of them have certain defects. There is an urgent need to develop fully automatic EC disassembly equipment with high automation, environmental protection, high processing efficiency and low energy consumption. If ECs are to be reused after disassembly, it is necessary to classify various functions and types of ECs first. Whether the sorted ECs still have certain utilization value can be tested by certain methods.

7 Challenges and perspectives

Although some research has been conducted on the non-destructive, green disassembly of key components on WPCBs and there are some practical applications, the following problems still exist.

(1) The design life of each type of EC is limited. At the time of recycling, although most of them are far from reaching their service life, it is unreasonable to reuse them according to their original design and function. Therefore, it is necessary to establish nondestructive testing methods and remaining life prediction methods and technologies for used critical devices as soon as possible. Considering stepwise utilization, under the premise of ensuring the safety of chip reuse, it gives full play to the advantages of the long life of ECs, and makes full use of the value of various key components.

(2) According to the current study, several considerations are proposed for the chip recycling process. First, in the disassembly and recycling processes, the board and chip temperature and heating rate must be maintained the same or similar as much as possible, to avoid the temperature difference in the heating process so that the chip in the disassembly process does not deform. Secondly, the disassembly of the ECs requires attention to remove moisture, to avoid the presence of moisture in the heating process which would result in damage to the internal structure of the chip. And the disassembled chips should also be stored in a dry environment, which is conducive to the subsequent recycling process. Finally, the process of

disassembling the chip from WPCBs is mostly performed under the condition that the PCB is exposed to air, so it is possible that the chip pins will be oxidized, which will lead to damage to the chip.

(3) The reliance on manual sorting needs to be reduced in post-disassembly processing. A refined sorting system can be developed later based on the Internet of Things, big data, image recognition and other technologies.

(4) During the disassembly of WPCB components, the solder is heated and melted, especially the lead-containing solder, which generates a large amount of toxic and hazardous gases containing a large number of particles, and special attention should be paid to the fume cleaning process during the disassembly process in the subsequent research.

Author contributions

Wenting Zhao: survey, data curation, writing-original draft, and visualization. Junqing Xu: manuscript supervision and data curation. Wenlei Fei: conceived the study. Ziang Liu: survey. Wenzhi He and Guangming Li: conceived the study, validated the manuscript, and supervised the research.

Conflicts of interest

There are no conflicts to declare.

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