



Review

Photocatalytic Materials Obtained from E-Waste Recycling: Review, Techniques, Critique, and Update

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Abstract: Waste-derived materials obtained from the recovery and recycling of electronic waste (e-waste) such as batteries and printed circuit boards have attracted enormous attention from academia and industry in recent years, especially due to their eco-friendly nature and the massive increment in e-waste due to technological development. Several investigations in the literature have covered the advances achieved so far. Meanwhile, photocatalytic applications are especially of interest since they maintain mutual benefits and can be used for H₂ production from solar water splitting based on semiconductor processing as a proper environmentally friendly technique for solar energy conversion. In addition, they can be utilized to degrade a variety of organic and non-organic contaminations. Nonetheless, to the best of the authors' knowledge, there has not been any comprehensive review that has specifically been focused on e-waste-derived photocatalytic materials. In this regard, the present work is dedicated to thoroughly discussing the related mechanisms, strategies, and methods, as well as the various possible photocatalysts synthesized from e-wastes with some critiques in this field. This brief overview can introduce modern technologies and promising possibilities for e-waste valorization, photocatalytic processes, and new photocatalytic degradation methods of eco-friendly nature. This paper discusses various e-waste-obtained photocatalytic materials, synthesis procedures, and applications, as well as several types of e-waste, derived materials such as TiO₂, ZnO, indium tin oxide, and a variety of sulfide- and ferrite-based photocatalytic materials.

Keywords: e-waste recycling; photocatalysts; electrocatalysts; nanomaterials; battery recycling

1. Introduction

Electronic waste (e-waste) refers to all components of any electrical and electronic equipment (EEE) that have been discarded without the intent of re-use. E-waste covers

a wide range of products—almost any household or industrial item with circuitry or electrical parts having a power source or battery supply. During the 20th century, EEE started to be widely commercialized, and many household appliances were introduced, including refrigerators, televisions, and washing machines. Ever since, the technological advancements combined with ease of accessibility resulted in the significant expansion of the electronics industry, making it as a crucial part of modern daily life. This became even more important with the introduction of information and communication technology (ICT) and the increasing use of mobile phones, personal computers, laptops and all kinds of gadgets [1]. This rapidly expanding and increasing use has led to a new environmental problem called e-waste, which contains large amounts of harmful and toxic substances along with precious metals. This serious threat can be turned into an opportunity with the proper management and implementation of new methods and reap significant financial and environmental benefits. Unfortunately, the world suffers from a substantial lack of industrial effort dedicated to recycling e-waste, especially in developing countries, and as such, only a very small fraction of discarded e-waste is recycled. In this regard, most techniques of e-waste valorization are focused on recovering precious metals, while various metals can be recovered from e-waste and some of them can be transformed into photocatalysts which can be used in numerous environmentally friendly applications, such as water remediation, the degradation of dyes, and solar cells. Numerous metal oxides can be extracted from e-waste and transformed into photocatalytic materials; however, the required recycling procedures are rather complex [2,3]. This review study focused on the high throughput production of various photocatalytic materials from e-wastes with a concentration on methods especially environmentally friendly strategies.

1.1. Global Status of E-Waste

Technological advances and the increased utilization of electronic tools due to growing levels of electronic waste and its inappropriate and insecure treatment and disposal through open burning or in dumpsites represent considerable hazards to the environment and threaten human health [4]. This is a huge and serious risk and should not be considered as an insignificant issue as it has been reported that global e-waste generation has grown to 44.7 million metric tons annually [5]. Unfortunately, only 20% of generated e-waste is collected and recycled, and the rest are incinerated or land-filled, which increases the risk of environmental pollution by toxic elements and other chemicals [5]. Despite the small share of recovered e-waste in the total waste (2%), it contains the highest amount of hazardous constituents, reaching ~70% [6].

In addition to the serious environmental hazards of e-wastes and the environmental benefits of recycling e-waste, e-waste has huge economic potential. The value of total raw materials present in e-waste (such as Fe, Cu, Al, Ag, Au, Pd, and plastics) was estimated to be approximately EUR 55 billion in 2016, which is a greater value than the gross domestic product (GDP) of most countries in the world in 2016 [5]. Actually, up to 60 elements from the periodic table exist among the various e-waste types and many of them are technically recoverable. In addition to the existence of precious metals such as gold, silver, platinum, and palladium in e-waste, these possess hazardous, rare earth, and scarce metals. The most popular hazardous species found in e-waste include various toxic chemicals (such as CFCs/chlorofluorocarbon or various flame retardants) and heavy metals (such as Hg, Pb, and Cd); hence, it is of utmost importance that e-wastes are systematically collected, treated, and recycled into valuable products. It should be noted that the environmental aspect of e-waste pollution as the fastest growing waste stream in the world is of great significance since, according to the Global Recycling Foundation, it has gradually become one of the biggest threats to the Earth because of its toxicity and hazardous components [5,7].

1.2. Importance of the Study and Aims

By considering the global status of e-waste, its adverse impact on environment, and the significant benefits of its proper management and recovery, it is of great importance

to gather all the key influential factors to study the subject of e-waste-derived materials. In this regard, the present study gives a comprehensive overview of the specific types of e-waste-derived materials in the category of photocatalysts as a solution to ever-increasing e-waste-induced environmental issues. This study is dedicated to identifying the possible photocatalytic materials that can be recycled from e-waste, their production scheme, involved factors, etc. with a special focus on techniques, critique, and their update. Additionally, the type of utilized e-waste was considered, since it plays a significant role in the recycling stage as each type of e-waste can be a source of specific materials, as was mainly observed in lithium-ion and other battery types, whilst printed circuit boards and the metallic scraps of e-wastes were investigated and may eventually be used for the production of photocatalytic materials. Unfortunately, information about the global state of e-waste recycling and the scale of recovery projects is limited and only a few countries have reported detailed information, mostly the U.S and China. Therefore, another goal is to highlight the advantageous and beneficiary aspects of e-waste recovery from both environmental and economical perspectives. This paper is also dedicated to presenting the challenges and techniques, their outcomes, shortcomings, and relevant parameters. The main gaps in this issue are related to finding more efficient and inexpensive ways to recycle e-waste and transform them into high-throughput photocatalytic materials. Overall, this study was designed to fully cover the advantages, the current state, technologies, influential parameters, and the main photocatalytic materials produced from e-waste recovery; it is hoped that this will pave the way for the development of more efficient methods for the improved production of photocatalytic materials from e-waste.

1.3. Photocatalytic Materials from E-Waste

There are numerous sources of e-waste, such as TVs, monitors, laptops, lamps, toasters, refrigerators, mobiles, and electronic gadgets; the usual e-waste sources and their approximate percentages are illustrated in Figure 1 [8]. Recently, e-waste became a sustainable source for a variety of nanomaterials as well as electrocatalytic and photocatalytic materials. In this regard, Figure 2 schematically presents the e-waste classification, the recycling management and its proximate amounts, and the major materials and elements that can be derived from a variety of e-wastes [6]. As can be seen, the recovered elements are mainly dependent on the type and composition of e-waste equipment, and it is usually precious metals, rare earth elements, metallic oxides, and photocatalysts that can be found in IT and telecommunication equipment [9]. The most preferred equipment for the production of photocatalytic materials through recycling are a variety of batteries, printed circuit boards, and integrated circuits (ICs) and mostly the photocatalytic metallic materials are recycled by pyrometallurgical and hydrometallurgical methods or a combination thereof after the suitable preparation steps (mechanochemical processes). Despite the suitability of these traditional pyrometallurgy and hydrometallurgy methods from different aspects, these could not maintain all the requirements for high throughput and the environmentally friendly recycling of e-wastes and they suffer from numerous limitations and drawbacks which will be discussed in the following sections.

Considering the environmental and economic impacts of e-waste recycling, the necessity to develop new methods and procedures for high-throughput recycling techniques is clear, especially for modern green industries and photocatalytic applications. Some of the e-waste recycling methods for the production of photocatalytic materials are considered green industries since these techniques prevent the inappropriate disposal of e-waste, leading to the release of noxious materials with devastating environmental consequences in addition to the loss of countless high-value materials [10]. The appropriate management of e-wastes through recovery methods extremely limits the exposure of toxicants, which can considerably affect the surrounding environment and living creatures; hence, these techniques are categorized under green and eco-friendly industry or technologies [6,11]. Additionally, most photocatalysis-related reactions and procedures are considered green technologies since they can potentially oxidize many toxic inorganic ions into their harm-

less upper oxidized state, so they can generally be used in the decontamination and degradation of organic pollutants, including dyes, pesticides, insecticides, herbicides, and fungicides, etc. [12,13]. It should be noted that green (technologies or industries) is an umbrella term that refers to the utilization of technology and science to decrease the adverse impacts of human development on the natural environment.

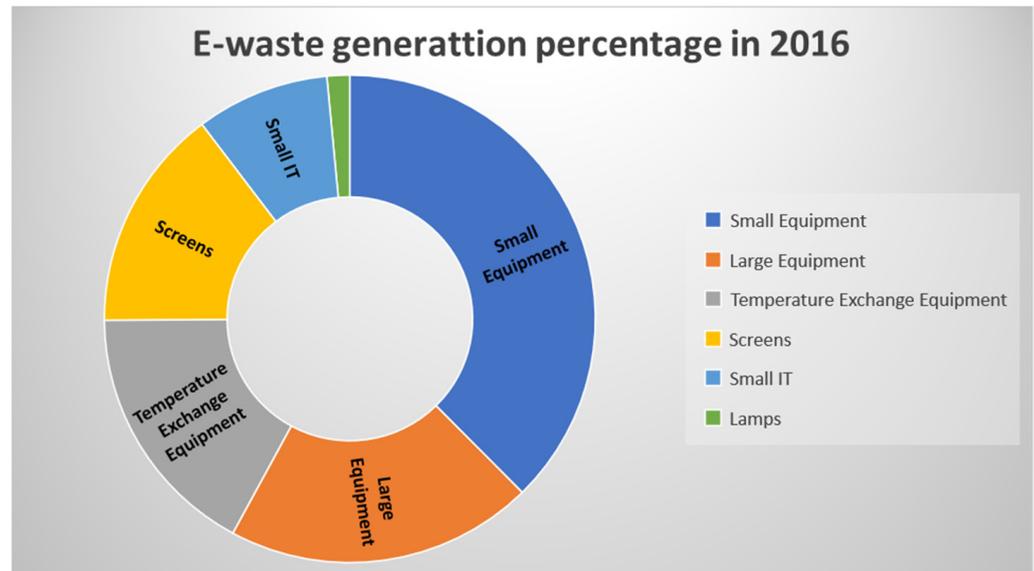


Figure 1. The major e-waste sources and their approximate percentages in 2016.

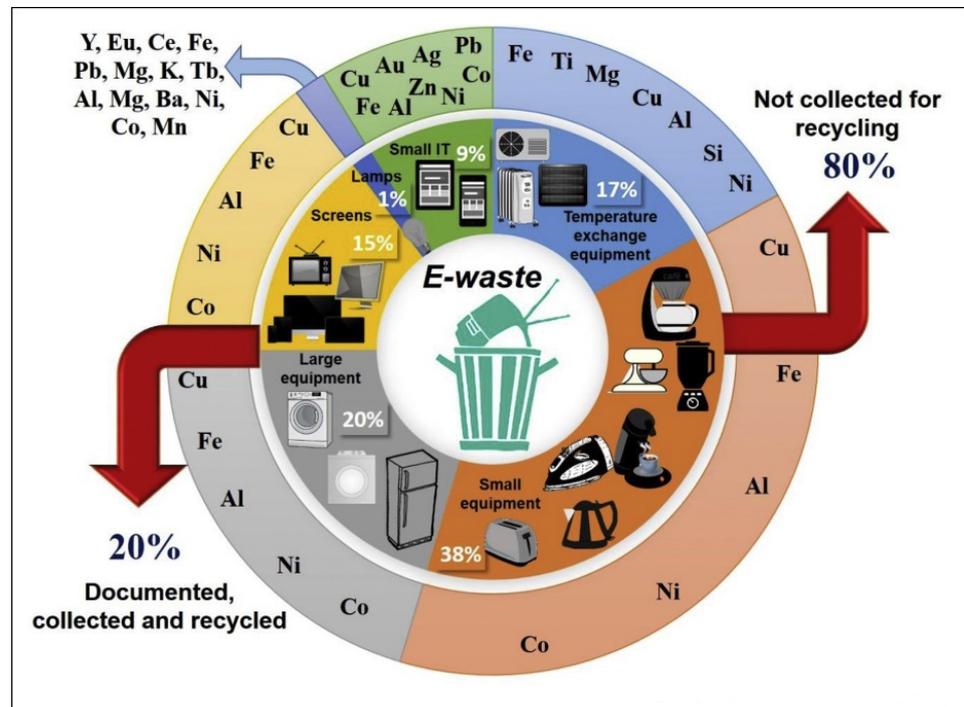


Figure 2. The schematic presentation of e-waste varieties and classification, the current management band, and their elemental compositions [6].

In addition to the existence of hazardous materials such as Pb, Hg, and Cd, there are a considerable amount of precious and rare earth elements, such as Pt, Au, Y, and Co in e-waste residues which can be used in photocatalytic applications. Additionally, due to the significance of metal-catalyzed procedures in the chemical industry, these e-waste-

extracted catalytic materials that are green in nature manifest immense potential economic and environmental benefits [14]; these materials are known as green catalytic materials since they have a nontoxic essence and utilize solar energy with the desired bandgap to absorb a wide range of the solar spectrum in order to degrade various contaminations, dyes, etc., into harmless outputs; for instance, they can be used in water remediation applications under sunlight [15]. However, the recycling and recovery procedures of e-waste-extracted catalytic materials are sometimes challengingly complex and unfortunately lead to the production of toxic by-products, high amounts of solvent, and excessive water consumption [16–18]. The environmentally friendly recycling of e-wastes for photocatalytic applications has general benefits and kills two birds with one stone, since the produced photocatalytic materials from e-waste recycling are used for H_2 fabrication via solar water splitting. In the photocatalytic procedure, the light energy is utilized to drive pairs of chemical reactions; when photocatalytic materials are exposed to light, a pair of excited electron/holes are produced because they are in an activated state. Finally, the electron and hole engage in a chemical reduction and oxidation reaction [19]; Figure 3 shows a simple photocatalytic procedure. Photocatalysis reactions include light and a semiconductor and the light-absorbing substrate (photocatalyst) that acts as a catalyst for a chemical reaction. These semiconductor-based photocatalysts can be successfully recycled from e-waste. Some factors should be considered in the fabrication of photocatalytic materials, such as having acceptable charge separation property, rapid charge transferring, a high absorption of light covering a large spectrum of waves, high chemical stability, low cost, and nontoxicity.

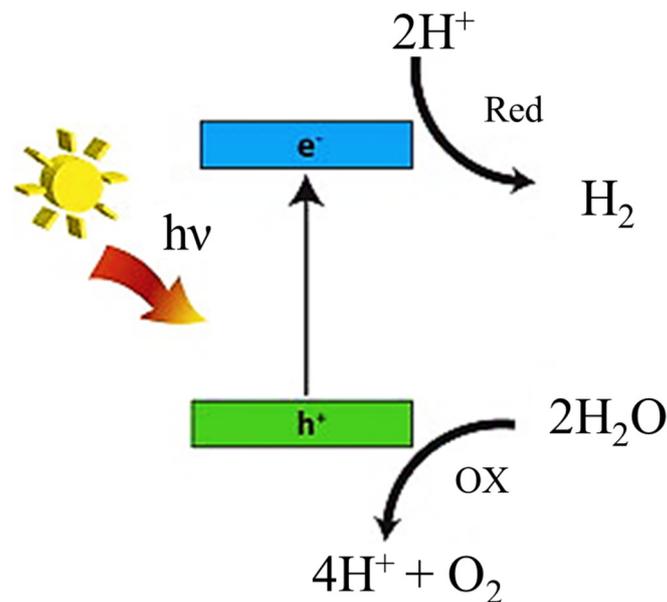


Figure 3. A simple photocatalytic procedure [19].

Numerous types of components can be recycled from e-waste, including circuit boards, hard disks, toner and ink cartridges, and batteries. The most important and initial steps during the recycling process can be, respectively, listed as (1) e-waste collection and transportation; (2) shredding and sorting; (3) dust extraction; (4) magnetic separation; (5) water separation; and (6) waste stream purification. A simple flowchart of the motherboard, CPU, and ceramic CPU recycling plant is illustrated in Figure 4, leading to the recovery of metals such as Au, Ag, Pd, Pt, Al, Fe, Cu, Ni, and plastic using several methods, including physical separation, hammer milling, leaching, electrowinning, and wastewater neutralization [20]. It should be noted that these methods are not completely environmentally friendly and they are not capable of simultaneously recovering multiple materials with a high recovery rate and satisfying selectivity.

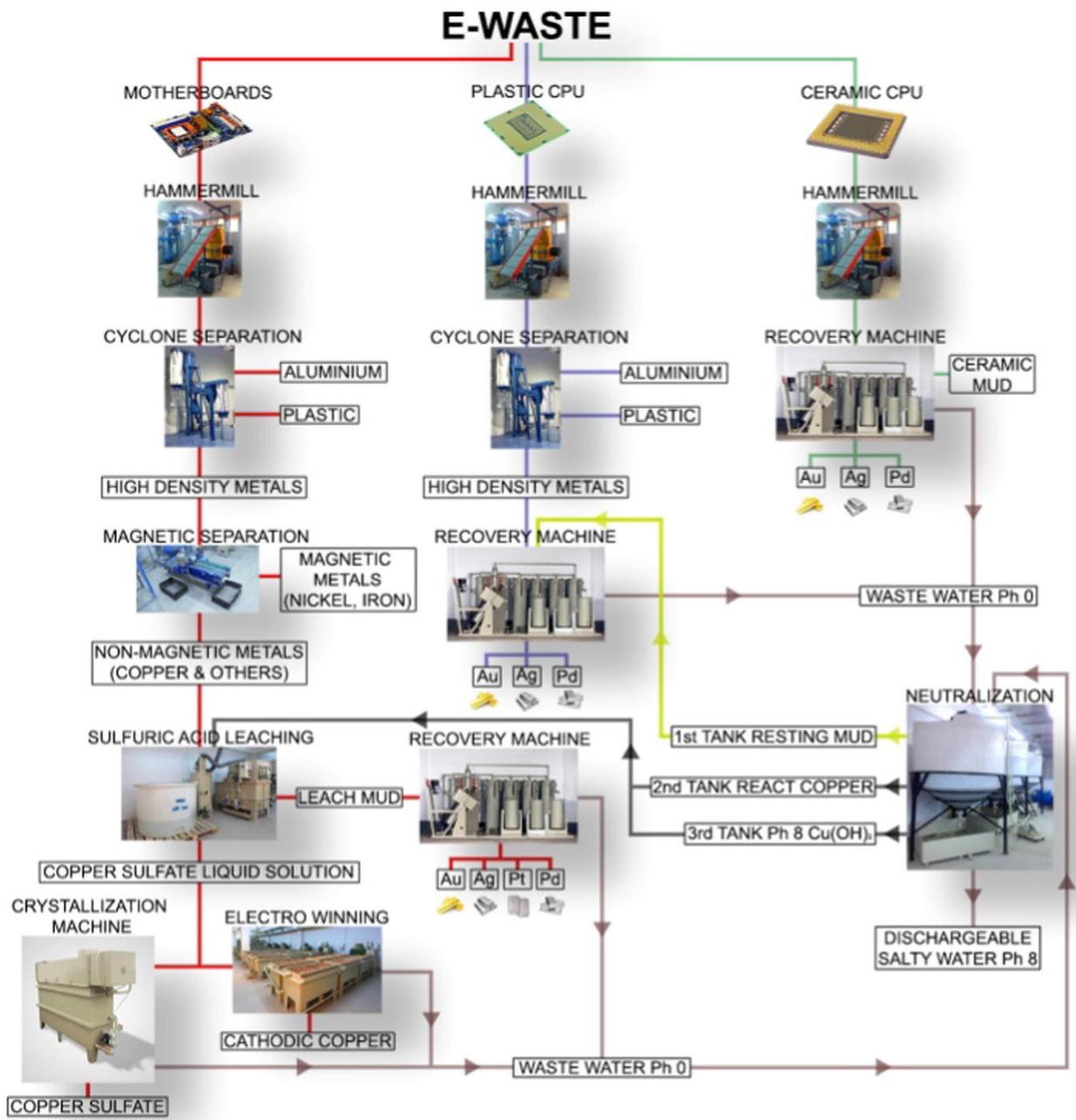


Figure 4. A simple flowchart of the motherboard, CPU, and ceramic CPU recycling plant [20].

Recycling techniques are generally categorized into two major groups, namely physical/mechanical recycling techniques and chemical recycling techniques. Additionally, other techniques such as vacuum metallurgy separation [21], bioleaching [22], and supercritical fluids oxidation–extraction [23] processes can also be used. Recently, Chen et al. [24] introduced a novel photocatalytic technique that can selectively recycle seven precious metals, including Ag, Au, Pd, Pt, Rh, Ru, and Ir, from various e-wastes. One of the advantages of this method is that it does not need the utilization of any strong acids or bases or toxic cyanide: it only requires light and photocatalysts such as TiO_2 . In addition, it can recycle more than 99% of the targeted elements of the e-waste after a simple reduction reaction, resulting in high purity ($\geq 98\%$) [24]. Niu et al. [25] successfully converted multilayer ceramic capacitors (MLCCs) (mainly composed of BaTiO_3 , Ag, Pd, Ni, and Sn) into a highly efficient photocatalyst through a one-step ball milling procedure, producing an Nb-Pb-codoped and a Ag-Pd-Sn-Ni-loaded BaTiO_3 nano-photocatalyst with superior photocatalytic efficiency. Considering the major recovery methods, in physical/mechanical processes,

the various metals and nonmetals that existed in e-wastes are released and separated through shredding, and crushing processes by crusher, pulverizer, classifier, and separator techniques. Subsequently, the high-voltage electrostatic separation is used to separate the mixture of metal powders. In the chemical recycling methods, the e-waste decomposes into beneficial chemicals and metals through chemical reactions [20]. The major chemical methods include gasification, pyrolysis, depolymerization, and hydrogenolytic degradation, leading to the separation of organic and metallic materials [26]. It is very common to use chemical methods in recycling printed circuit boards (PCBs), which are one of the most abundant types of e-waste. PCBs contain numerous electronic components (ECs), including capacitors, resistors, relays, and integrated circuits (ICs), so they have a heterogeneous mixture of metals, nonmetals, and other toxic substances. The metal content of PCBs is high, including ~30% Cu, 0.05% Ag, 0.01% Pd, 0.03% Au, 10–20% solder Pb, 1–5% Fe, and 1–3% Ni. Fortunately, the purity of these metals in PCB is considerably higher than that of rich minerals, making it very attractive and economic for recycling [27]. However, PCB recycling usually leads to the production of a lot of dust (toxic gases, such as dioxin, lead fume, etc.) and some materials cannot fully be recovered, so the procedure needs to be sealed off and the resulting industrial dust should be actively avoided. During PCB recovery, usually the nonmetallic materials cannot be recycled and an enormous amount of capital investment is generally needed. It was known that chemical recycling methods are favorable candidates for PCBs; for instance, Veit et al. [28] utilized magnetic and electrostatic separation followed by the electrowinning process for recycling the metals from PCB scarp and they successfully recycled Pb, Sn, and Cu. Additionally, ionic liquids, such as 1-ethyl-3-methylimidazolium tetrafluoroborate [EMIM⁺][BF₄⁻], can be used to extract the valuable materials from PCB e-waste [29]. One of the preferred chemical methods is pyrolysis which can be used to recycling PCBs, as Quan et al. [30] performed a pyrolysis process on a fixed-bed reactor and could recycle metals, glass fibers, and pyrolysis oil from PCBs. Despite the advantageous nature of these methods, they are not completely categorized in the group of environmentally friendly techniques, so much attention should be paid to avoid environmental issues such as by the utilization of furnace cupola, gas-washing towers, suitable post-processing, proper waste and by-product managements, etc.

The other important e-waste that can be recycled are batteries, which consist of an anode and a cathode within an electrolyte along with the separators and external case. There are different types of batteries, each of which has its own recovery processes, but they are mostly recycled through mineral processing, hydrometallurgical processes, and pyrometallurgical processes [31–33]. The recovery products mainly include metallic alloys and compounds, or solutions containing metallic ions. Mineral processing separates the materials according to their conductivity, density, magnetic behavior, etc., and is usually applied as a pre-treatment to concentrate the metallic constituents following hydrometallurgical or pyrometallurgical processes [34,35]. Recently, lithium-ion batteries (LIBs), because of their vast application in electrical vehicles (EVs) and laptops, have received significant attention, and are mainly composed of a high percentage of hazardous heavy metals, aluminum, copper, transition metal oxides and phosphates, graphite, organic electrolytes with toxic lithium salts, polymers, plastics, and metallic cases [36–38]; Figure 5 shows the typical flowchart of LIB recycling. In LIB recycling, both physical and chemical processes should be used due to the complicated nature of LIBs, and before any recovery processes, the batteries should be discharged to prevent any fire and explosion occurrence. Unfortunately, the recycling of lithium-ion batteries is risky due to several reasons, including the fact that they are volatile and could be a source of fire hazards, in addition to the challenging recovery of Li and other rare metals such as Co in LIBs, which requires considerable, tedious, and expensive mechanical pre-treatment and separation steps, and sometimes, the recovered material not perform as well as the virgin material.

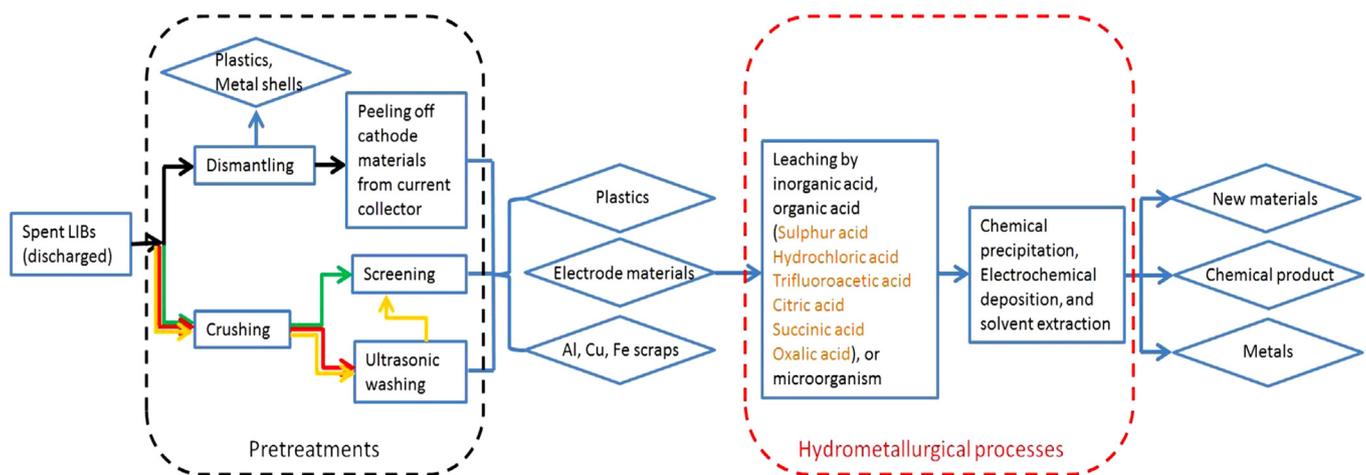


Figure 5. The typical flowchart of the recycling process of lithium-ion batteries (LIBs) [36].

2. Methodology

The purpose of the present work was to conduct a comprehensive review of the published peer-reviewed journal articles and book chapters according to the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses, providing a source of information on electronic waste recycling for the production of photocatalytic materials. Additionally, some reports and monitoring results from the U.S., China, Brazil, and worldwide data about e-waste conditions were included. In the literature search, Springer, Scopus, ScienceDirect, and other databases were used, and two authors independently performed the online search, study selection, and data extraction. The reference lists of other journal papers and previous reviews were also considered to identify eligible investigations not located using the database searches. We conducted a database search for relevant papers from between 2000 and 2022 which were identified based on titles and abstracts. The following search terms were used: electronic waste recycling, recovery, waste-derived materials, photocatalyst, metal scrap, e-waste separation, battery recycling, printed circuit boards recycling, photocatalytic materials, metallic oxide photocatalysts, metallic sulfides, biohydrometallurgy, etc. The goal of this comprehensive review was to highlight the importance and advantages of e-waste recycling in the production of photocatalytic materials as well as to give a brief overview of the traditional and modern techniques to produce various types of photocatalysts whilst focusing on the challenges, potential gaps, and future perspectives in this research field.

3. Results and Discussion

3.1. Strategies of Metal Oxide Recovery

Generally, e-waste recovery and recycling procedures mainly involve metal oxide-based materials; hence, it could be very useful to thoroughly analyze the conditions, procedures, and types of used waste. The waste materials can be categorized into three main groups, namely batteries, used instruments, and wastes and sludges. Through the utilization of several methods, a variety of metallic nanoparticles (NPs) such as ferrites and metal oxides could be recovered by recycling these three categories of waste materials. Meanwhile, the most well-known methods are hydrometallurgical and pyrometallurgical approaches. Figure 6 shows the processing steps of these two methods to obtain metallic species from several wastes. It should be noted that, despite their vast utilizations, hydrometallurgical and pyrometallurgical approaches are regarded as traditional methods and still suffer from numerous inherent weaknesses, including minor single-step separation factor, discontinuity of techniques, high chemical consumption, toxic by-products, high costs, complicated procedures, and a poor working environment.

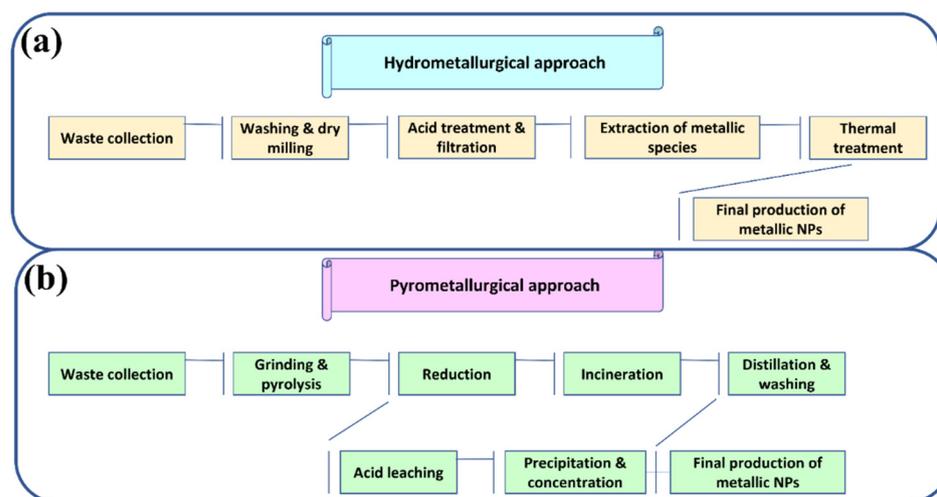


Figure 6. Process steps of (a) hydrometallurgical and (b) pyrometallurgical approaches to recover metallic species from various wastes.

In addition to the techniques utilized in the recycling of various materials from e-waste, the recovery rate and the efficiency of the methods are of the utmost importance and most investigations and industrial projects are trying to increase the recovery rate as much as possible in addition to ensuring their economic productivity; Table 1 seeks to provide a viewpoint about some techniques and their efficiency in the recycling of various types of e-waste. As can be inferred from Table 1, just a few procedures can attain 100% recovery rates and most of them are incapable of simultaneously recovering multiple materials with high selectivity from the e-wastes, whilst the type of e-waste is also another limiting factor that should be considered.

Table 1. Different recovered materials from e-wastes by the utilization of various methods and their efficiency.

E-Waste	Recovered Material	Method	Recovery Rate (%)	Ref.
spent Zn-MnO ₂ alkaline batteries	ZnO	liquid–liquid extraction	98	[39]
spent alkaline batteries	ZnO	one-pot chemistry	Up to 98	[40]
lithium-ion batteries	lithium	acid leaching	99.4	[41]
spent rechargeable batteries	Co, Mn, Cd	hydrometallurgical, liquid–liquid extraction	100	[42]
spent rechargeable batteries	Al	hydrometallurgical, liquid–liquid extraction	67	[42]
spent rechargeable batteries	Cu, Ni	hydrometallurgical, liquid–liquid extraction	95	[42]
PCBs	Al, Zn, Cu	biohydrometallurgy	77, 86, 97	[43]
PCBs	Cu, Al, Ni, Zn	biohydrometallurgy	86.2, 100, 100, 100	[44]
PCBs	Cu, Ni	pyrometallurgy coupling bioleaching	49, 100	[45]
PCBs	Cu	high temperature pyrolysis	91.7	[46]
spent Li-ion battery	cobalt ferrite	sol–gel–hydrothermal	-	[47]
PCBs	Cu	vacuum pyrolysis	53–100	[48]
PCBs	Cu, Pb, Sn	crushing and electrostatic separation	-	[49]

3.1.1. Hydrometallurgical Approaches

Commonly, metallurgical e-waste processing is performed through the smelting of waste parts using heat, entitled pyrometallurgical processing, while dissolving them in the relevant solvent or liquid solution called hydrometallurgical processing. After these methods, the resulting compound was refined according to its chemical properties either by currents and voltage, i.e., electrolytic techniques or through precipitation [20]. The

hydrometallurgical approach includes several steps, the dismantlement and collection of life end products, washing and cleaning with water to remove all undesirable materials, alkali/alkaline salts, extraction, thermal treatment, and filtration [50]; Figure 7 illustrates a detailed flowchart for hydrometallurgical processes utilized for the recovery of E-wastes. Conventionally, the hydrometallurgical approaches were applied for recovering the precious metals from mineral ores, but they can also be used for recycling waste electric/electronic equipment (WEE) through acid or the caustic leaching of selective dissolutions of the targeted metals [51]. Subsequently, the solution with the targeted metallic species and possible impurities is further refined, concentrating the metallic compounds by solvent extraction, adsorption, or ion exchange processes [2,52,53]. Eventually, by the utilization of electrorefining or electrochemical reduction reactions, the metallic target material is recycled from the E-waste. The hydrometallurgical approach is the most adept and efficient method to recover metallic species since it can control the impurities, and additionally, it is among the most eco-friendly (any processes that are not harmful to the environment or even trying to help the environment and the Earth’s ecosystem) and economic recovery processes [54]. The efficiency of hydrometallurgical e-waste recovery is reported to be very high, ranging between 82% and 100% [51]; for instance, leaching through thermal transformation to recover metallic materials from PCBs can lead to recovery efficiencies of up to 93.56%, 65.07%, 92%, and 95.52%, respectively, for Cu, Zn, Pb, and Sn [55]. The other reported example is the room temperature recovery of Sn from PCBs through the hydrometallurgical route followed by electrodeposition which leads to a 100% recovery rate after just two hours of treatment [56]. In hydrometallurgical processes, the targeted metal should be properly leached into solutions of desired concentration involving mostly acids, such as hydrochloric acid, nitric acids, strong sulfuric acids, aqua regia, and a few alkalis. There are different types of leaching processes, such as cyanide leaching, acid and alkaline, thiosulphate, thiourea, and halide leaching. Then, the metallic compound is further processed, respectively, by electrorefining, precipitation, cementation, adsorption, solvent extraction, and/or ion exchange [57]. Along with many beneficial aspects of hydrometallurgical methods, they still have many issues that should be considered and solved, such as high electricity consumption, the utilization of toxic chemicals, high water and solvent consumption, the occurrence of severe corrosion in components, the discontinuity of procedures, limitations on the simultaneous recycling of several elements, large volumes of secondary waste by-products which necessitates additional processing, etc.

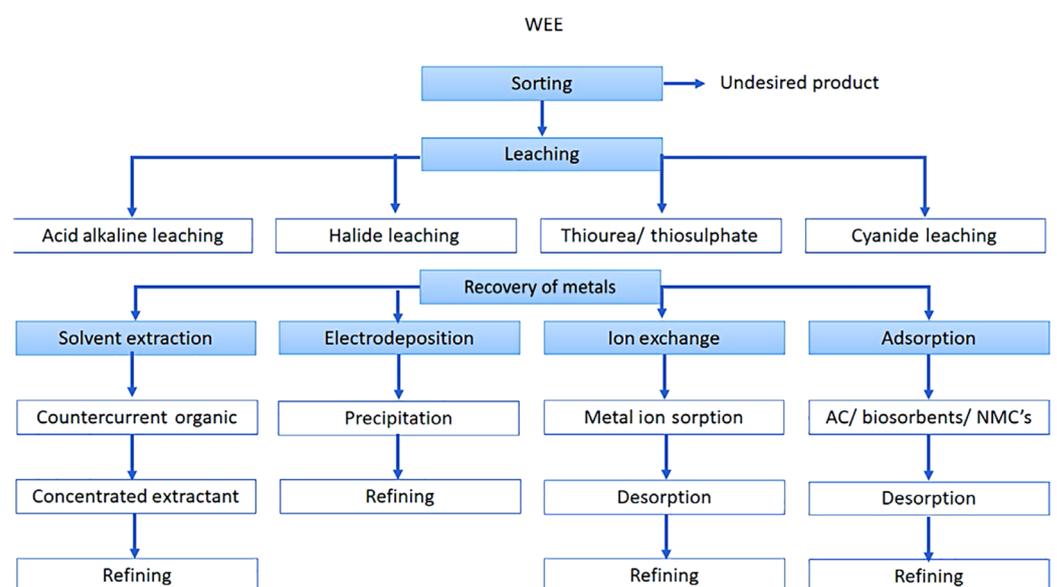


Figure 7. The detailed flowchart for hydrometallurgical processes utilized for the recovery of waste electric/electronic equipment (WEE) [51].

3.1.2. Pyrometallurgical Approaches

As a traditional process, the pyrometallurgical approach is the most popular and extensively used method for e-waste recovery. Pyrometallurgical processes offer advantages such as the enhancement of purity of the final metal products, high production rates, and the possibility to control and increase the temperature to activate reactions that are not thermodynamically possible at low temperatures [58,59]. It was shown that the utilization of pyrometallurgical processes for recycling precious metals from mobile phone-printed circuit boards can lead to high recovery rates greater than 99% which can also be increased by a combination of traditional incineration processes and wet processes [60–62]. Although the pyrometallurgical approach has many advantages, it is not an economic method and consumes high levels of energy and materials, forms toxic or harmful fumes and gases, and unfortunately, the metal recovery of individual species through the pyrometallurgical method is challenging. Another limitation of pyrometallurgical methods is that they cannot be developed for small-scale commercial operation. Additionally, these methods sometimes lead to the loss of precious recovered materials in high-temperature smelting furnaces and they have some limitations in terms of the full recovery of materials with a high affinity towards oxygen since they are usually bound as an oxide in the slag [63]; for instance, the slagging of lithium requires a substantial effort to be solved [36,64]. In some cases, reactor turbulence issues can also be found in pyrometallurgical techniques which is due to the presence of various gases and leads to material accumulation at the bottom of the reactor [65]. Furthermore, as traditional methods, pyrometallurgical techniques are unable to simultaneously recover multiple materials with acceptable selectivity and purity.

Pyrometallurgical processes involve incineration, utilization of arc furnaces, and high-temperature roasting with selective gases, and are applicable for both metallic and nonmetallic wastes [20]. The main steps of pyrometallurgical treatments, respectively, are pyrolysis, reduction, distillation, and incineration [66]. The pyrometallurgy procedures can be performed under vacuum (vacuum metallurgy) or with the presence of a variety of gases under atmospheric pressure (pressurized metallurgy). It should be noted that vacuum metallurgy is preferred due to its eco-friendly nature, and there is no need to use tail gas treatment equipment [67]. Furthermore, since the metals manifest lower boiling points under vacuum, their recycling by vacuum mining leads to a significant energy reduction compared to traditional thermal mining operations since the electric energy consumption of vacuum metallurgy separation (both heating and vacuum process) for the recycling of 1 t waste Ni-Cd batteries at an industrial scale is at maximum USD 229 while its revenues reach to at least USD 1308 [68].

3.1.3. Biotechnological Approaches

Biotechnological techniques for recycling e-waste may offer more auspicious alternatives than the traditional pyrometallurgical and hydrometallurgical technologies in metal recovery and urban mining. The most appealing aspect of these methods is their selectivity toward critical and valuable metals, so they can be employed in the bioremediation of heavy metals owing to their high biosorption abilities [69]. Additionally, these biotechnological methods are cost-effective and are source of lower environmental concern [70]. During biohydrometallurgical and bioleaching methods, living organisms such as fungi or bacteria are utilized to leach or dissolve metals from a complex matrix, and hence, microorganisms play a key role in the oxidation and leaching processes of metals. The biohydrometallurgy processes can be performed both directly and indirectly. In direct biohydrometallurgy, microorganisms engage in the recovery process through enzymatic reactions, while during indirect biohydrometallurgy, microorganisms participate only in the metal leaching process once they have been separated from their matrix. Biohydrometallurgical and bioleaching methods attract much attention due to their numerous advantages, including a reduction in energy cost (no need for high temperatures), nontoxicity, environmentally friendly nature, and the possibility of the selective extraction of metals [70]. It was reported that bioleaching is successfully used on a commercial scale to recover metals from sulfidic ores while it is not

fully matured for the case of e-waste recycling and remains in the stage of infancy [71]. The bioleaching or biomining process employs a direct metabolism or by-products of microorganism reactions to solubilize a metal sulfidic ore or e-waste into an aqueous solution, and is usually commercially adopted for the extraction of base metals, such as copper, tin, or zinc [72,73]; Table 2 lists some of the studies about the bioleaching of metals from electronic wastes along with the utilized methods, microorganisms, leaching efficiencies, and the type of e-waste reproduced from [70]. However, whilst the beneficiary aspects of biotechnological techniques are high, they have some limitations which prevent their widespread utilization, such as cyanide generation, reduction in recovery rate due to diffusion issues and secondary mineral precipitation, lower recovery rate, low industrialization, downcycling due to loss of various metals, limited lifespans of microorganisms, high operational costs, need for organic solvents, longer operation period, dependency on atmospheric conditions, etc. [74,75].

Table 2. The bioleaching recovery of metals from e-wastes along with utilized microorganisms, leaching efficiency, the type of e-waste, and the used techniques, reproduced from [70].

E-Waste	Microorganisms	Leaching Efficiency (Metal) (%)	Technique	Ref.
Mesophilic bacteria				
Autotrophs				
PCBs, scraps, e-wastes	<i>A. ferrooxidans</i> + <i>A. thiooxidans</i>	90 (Al, Cu, Ni, Zn)	Rotary shaker, flasks	[76]
	<i>A. ferrooxidans</i>	37 (Cu)	Shake flasks	[77]
	<i>Acidithiobacillus</i> sp. + <i>Leptospirillum</i> sp.	100 (Cu, Ni)	Erlenmeyer shake flasks	[78]
	<i>Acidithiobacillus</i> sp. <i>Gallionella</i> sp. + <i>Leptospirillum</i> sp.	95 (Cu)	Shake flasks	[79]
	<i>A. ferrooxidans</i>	98 (Cu)	Erlenmeyer shake flasks	[80]
TV circuit boards	<i>A. ferrooxidans</i> + <i>L. ferrooxidans</i> + <i>A. thiooxidans</i>	89 (Cu)	Erlenmeyer shake flasks	[81]
Heterotrophs				
PCBs, scraps, e-wastes	<i>C. violaceum</i> , <i>P. fluorescens</i> , <i>P. plecoglossicida</i>	68.5 (Au)	Shake flasks	[82]
Waste mobile phone PCBs	<i>C. violaceum</i>	13 (Au); 37 (Cu)	Shake flasks	[83]
	<i>C. violaceum</i>	11.31 (Au)	Shake flasks	[83]
	<i>C. violaceum</i>	insignificant (Au)	Conical shake flask	[84]
	<i>C. violaceum</i>	20–30 (Au)	Shake flasks	[85]
Moderately thermophilic bacteria				
Electronic scrap	<i>S. thermosulfidooxidans</i> + <i>Thermoplasma acidophilum</i>	86 (Cu); 74 (Ni); 80 (Zn); 64 (Al)	Column bioleaching	[86]
	<i>S. thermosulfidooxidans</i> + <i>Sulfobacillus acidiphilus</i>	78 (Cu); 78 (Ni); 74 (Zn); 85 (Al)	Shake flasks and lab-scale column reactor	[87]
	<i>S. thermosulfidooxidans</i> + <i>acidophilic heterotrophic bacteria</i>	89 (Cu); 81 (Ni); 83 (Zn); 79 (Al)	Shake flasks	[88]
Fungi				
PCBs, scraps, e-wastes	<i>A. niger</i> + <i>P. simplicissimum</i>	100 (Al, Cu, Zn, Ni)	Rotary shaker, flasks	[76]
Electronic scrap	<i>P. chrysogenum</i>	97–98 (Cu)	One-step leaching with combined growth and leaching phases	[89]

3.2. Photocatalytic Materials from E-Waste

A lot of photocatalytic materials can be extracted from e-wastes, especially after doping with transition metals and photocatalysts. A normal photocatalysis process includes these basic steps: (i) generation of photoexcited electron-hole pairs by solar illumination of photocatalyst; (ii) separation of charge carriers; and (iii) after charge carrier separation, charge transferring done on respective catalytic sites/surface in order to induce redox reactions [90]. It should be noted that the reduction and oxidation potential of photoexcited electron-hole pairs relies upon the positions of conduction band minimum and valence band maximum [90]. The photocatalytic materials produced from e-waste can have some limitations such as low solar energy utilization and a high rate of charge recombination that should be highly considered.

The e-waste-derived materials include various metallic oxides and sulfides, carbon-based materials, biomass-templated materials, carbon quantum dots (CQDs), and most importantly, TiO₂ and ZnO [91]. In addition, noble metals (such as Pt, Au, Ag, etc.) can be derived from e-waste and subsequently utilized as co-catalysts in photocatalytic water splitting, CO₂ reduction, and other photocatalytic applications due to the high mobility of their charge carriers, transparency towards the light, and high density of active sites [90]. Photocatalytic materials have numerous applications such as water splitting, CO₂ conversion, pollutant degradation, and even bacterial inactivation. In semiconductor-based photocatalysis processes, heterojunctions are regarded as an effective architecture approach to mitigate the limitations of bare semiconductors [90]. Meanwhile, S-scheme and Z-scheme heterojunctions usually offer a higher redox ability and broaden solar energy utilization compared to traditional photocatalytic systems. During step-scheme (S-scheme), a reduction and oxidation photocatalyst happens in staggered band arrangement with Fermi level differences [90], while Z-scheme heterojunctions have two connected semiconductor photocatalysts that are able to keep the electron-hole pairs with proper reduction/oxidation abilities on active regions [90,92–94].

According to the literature, TiO₂-based materials are considered the most widely used photocatalysts with many green applications (waste water remediation [95,96], dye degradation [97], solar cells [98], etc.) and have many advantages, such as the ability to absorb visible and UV light, biological and chemical inertness, low cost, etc. [99,100]. Additionally, ZnO- and graphitic carbon nitride (g-C₃N₄)-based materials are among the most popular photocatalysts, ZnO-based nanostructures are low-cost, nontoxic, and more adept in the absorption of the solar spectrum compared to TiO₂ [101]. The g-C₃N₄-based materials having a visible-light activity, with a straightforward synthesis process from low-cost materials, chemical stability, and a unique layered structure which are also among the attractive photocatalysts [102]; in the following, photocatalytic materials from e-wastes are discussed in detail.

3.2.1. TiO₂-Based Materials

As the most commonly used photocatalyst material, TiO₂ has many applications, such as water splitting, hydrogen evolution, and photodegradation. Despite the vast utilization of TiO₂ as a successful photocatalytic material, it still has some drawbacks, for instance, unfortunately, its handling is difficult, its photocatalytic reaction is slow, its application in some cases is limited due to photocatalyst decomposing issues, TiO₂ has high charge recombination, it needs to be doped with other materials and the very low photo-inefficiency of the TiO₂ catalyst only covers 5% of the solar spectrum [103,104].

The recycling of Ti and Ti-based materials from e-waste can be performed through numerous techniques, such as Ti smelting and Kroll methods [105]. Unfortunately, despite the high efficiency (even up to 100%) of the strong acids in the leaching process [106], their extensive use is a critical issue in TiO₂ recycling. Other challenges in recycling the waste-derived photocatalytic materials are the dissatisfactory control over the resulting structure and poor reproducibility that is a significant problem since a few variations lead to significant changes in photocatalytic performance [107,108]. The multilayer ceramic

capacitors (MLCCs) (Figure 8) having BaTiO₃, Pd, Ag, Ni, and Sn (Figure 8) are potential e-waste for recycling TiO₂, but the recycling process through an environmentally friendly and efficient separation process is challenging. In this regard, Niu et al. [25] utilized a one-step ball milling process to attain an Nb-Pb-co-doped and Ag-Pd-Sn-Ni-loaded BaTiO₃ nano-photocatalyst, manifesting efficient H₂ generation, RhB degradation, and superior photocatalytic activity with approximately four times the commercial BaTiO₃. Note that BaTiO₃ is generally used to degrade organic pollutants and split the water [109,110]. Niu and Xu [111] successfully produced a Nb-Pb-co-doped and Pd-loaded TiO₂/BaTiO₃ heterostructure by the in situ synthesis of MLCCs through the facile chlorination-leaching process, showing great photostability and reusability due to Nb-Pb co-doping, heterostructure formation, and the Pd loading. Figure 8 shows the MLCC structure having many BaTiO₃ dielectric layers and stacked internal electrodes. In Figure 8, the simple chlorination-leaching process which resulted in the high throughput formation of Nb-Pb-co-doped and Pd-loaded TiO₂/BaTiO₃ heterostructure is shown [111]. The chlorination step was performed in a quartz tube furnace in which NH₄Cl and scrap powder with determined mass ratios of (0.5–4):1 was mixed and then heated at 500 °C for 30 min under air. In the course of the chlorination process, Ag, Sn, and a part of BaTiO₃ (doped with Nb and Pb) were involved in a reaction with the presence of HCl to generate SnCl₄, AgCl, BaCl₂, and TiO₂ (doped with Nb and Pb). The resulting SnCl₄ vaporized into the gas phase and was then collected in the condensing zone. The residual products and unreacted Pd remained in the residues. Subsequently, the residues were sequentially leached in the solution of distilled water and Na₂S₂O₃ in order to separate BaCl₂ and AgCl. Eventually, the Nb-Pb-co-doped and Pd-loaded TiO₂/BaTiO₃ heterostructure was manufactured. During the photocatalytic H₂ evolution of the samples, the simulated sunlight photocatalytic H₂ generation in the commercial TiO₂ and bare TiO₂/BaTiO₃, respectively, were ~42 and ~96 μmolg⁻¹h⁻¹. The TiO₂ sample (NH₄Cl/scrap:4) has the greatest H₂ evolution rate, an enhanced activity which can be related to co-doping with Nb-Pb, enhanced the visible light absorption, and has effective charge separation [112,113]. Niu and Xu [111] proposed a novel method for the in situ fabrication of Nb-Pb-co-doped and Pd-loaded TiO₂/BaTiO₃ nanostructured heterostructures from e-waste (multilayer ceramic capacitors) by a chlorination-leaching route. TiO₂-based photocatalysts from e-waste can be a great option to solve environmental pollution [114]. The fabrication of the TiO₂/BaTiO₃ heterostructure led to the improvement of photocatalytic H₂ activity due to its more potent charge separation. It was reported that TiO₂/BaTiO₃ heterostructure has superior photocatalytic activity toward H₂ evolution and organic degradation [115,116]. TiO₂/BaTiO₃ (NH₄Cl/scrap: 0.5) shows the most photodegradation efficiency with approximately 19.13 and 8.91 times greater than commercial TiO₂ and TiO₂/BaTiO₃ specimens. The photocatalytic degradation of RhB was also analyzed under simulated sunlight. Even though all the samples exhibited favorable photocatalytic activity toward RhB degradation, it was seen that the catalyst had a negligible impact on the degradation of RhB [111].

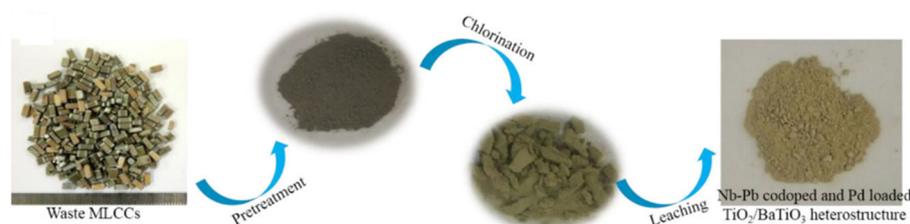


Figure 8. The multilayer ceramic capacitors (MLCCs) along with their constituents, including the in situ preparation procedure of Nb-Pb-co-doped and Pd-loaded TiO₂/BaTiO₃ heterostructure, derived from waste MLCCs [111].

Niu et al. [117] proposed a new approach to magnetically generate core-shell Z-scheme Nb-Pb-co-doped BaTiO₃/Ni-Pd@g-C₃N₄ photocatalysts using the ceramic capacitor e-waste for H₂ production. Firstly, by a simple ball-milling procedure, the waste ceramic capacitors

were converted to Nb-Pb-co-doped BaTiO₃/Ni-Pd-Ag-Sn nanoparticles, then g-C₃N₄ was coated on these nanoparticles leading to the production of a core-shell structure. These nanosized photocatalyst powders can make some problems during the liquid-phase reactions of a photocatalysis process. It should be noted that the Ni-Pd operated as the electron mediator, and the Ag-Sn could also facilitate the electron transfer in the Z-scheme structure. In this regard, a series of Z-scheme heterojunction structures with various mass fractions of g-C₃N₄ were constructed [117]. Eventually, the produced special Z-scheme photocatalyst presented exceptional photocatalytic H₂ evolution activity. In addition, the constituent Ni caused an excellent magnetically separable property in the photocatalyst.

3.2.2. ZnO-Based Materials

ZnO was considered the alternative photocatalyst material to TiO₂ since it has similar bandgap energy and even higher absorption proficiency toward sunlight irradiation [101]. It was reported that the waste-derived ZnO nanocomposites presented exceptional photocatalytic activity, especially towards a variety of organic dyes such as MB, RhB, and malachite green under UV illumination [118–120]. Hence, ZnO is a great and promising candidate for treating environmental contamination, specifically in organic wastewater remediation [121]. Unfortunately, ZnO photocatalysts have also some limitations which reduce its applications, including a high recombination rate of photo-induced charge carriers, insufficient stability, a low rate of sunlight utilization, limited photon absorption (just UV region), and photocorrosion due to light-unsteadiness, etc. [122].

Generally, ZnO-based materials are recovered through pyrometallurgy and hydrometallurgy procedures [123]. Due to the rapid technological development across the world, the utilization of batteries has increased, and Zn-C and Zn-Mn batteries, as the commonly used types of batteries, are mostly used in small devices which can be regarded as secondary resources for some valuable elements such as Zn. ZnO nanoparticles (NPs) could be recycled from the spent Zn-Mn dry batteries via high-temperature evaporation-separation and oxygen control oxidation in which air acted as the carrier gas and oxidizer [124]. In addition, ZnO NPs with a variety of morphologies can be generated from the spent Zn-Mn batteries through vacuum evaporation and oxygen control methods [125]. The morphology of ZnO NPs in this method can be controlled and adjusted by the O₂ oxidizer concentration, N₂ conveyor, type of substrate, calcination temperature, and the distance of condensing. It was demonstrated that increasing the aperture-size barbed wires from 200(75) up to 500(25) can promote the extraction efficiency from ~75% to ~92%. The pressure has no direct influence since 1, 3, and 10 KPa pressure, respectively, led to ~83, 91.5, and 87% extraction efficiencies. As an example, the nanotetrapod ZnO morphology with photocatalytic properties can be fabricated on a glass plate under the conditions of 1123 K temperature, 12.5% oxygen content, and with a nitrogen flow rate of 21 L min⁻¹ [125]. Figure 9 schematically illustrates the ZnO recycling process from Zn-Mn batteries by high-temperature evaporation-separation and oxygen control oxidation method [124]. There are some problems during the process, for instance the low evaporation and rapid oxidation rate of Zn may mix the ZnO with other impurities in the crucible. The combination of physical and chemical methods can considerably slow down the Zn oxidation rate and lead to suitable Zn dispersion during the evaporation process [124].

In another study, Maroufi et al. [126] recycled waste Zn-C batteries via a facile homogeneous precipitation-calcination method and successfully synthesized two-dimensional (2D) ZnO porous nano-sheet photocatalysts for the photodegradation application of methylene blue/MB aqueous solution under UV-Vis exposure. The produced ZnO nano-sheets had a thickness of up to 100 nm. Firstly, the Zn foil pieces from Zn-C batteries were placed in an HNO₃ solution and stirred at room temperature. Subsequently, the mixture was diluted by adding potassium hydroxide solution in order to attain a crystalline precipitant in gray color. The resulting crystalline phase had a hydroxide nitrate hydrate (Zn₅(OH)₈(NO₃)₂(H₂O)₂) composition, and this phase transformed into ZnO nano-sheets after calcination at 700 °C; Figure 10 shows the microstructure of the resulting porous ZnO nano-sheet [126]. Figure 10a,b clearly exhibit the production of ZnO porous nano-

sheets morphology for which TEM and HRTEM (Figure 10c,d) manifested the high level of porosity in these ZnO photocatalysts produced from the attachment of nanoparticles. The presence of rings in the SAED pattern in Figure 10e demonstrates the formation of crystallized nano-sheets. It was demonstrated that a prolix calcination procedure can support the growth of crystals, but on the other hand, it makes the agglomeration step longer.

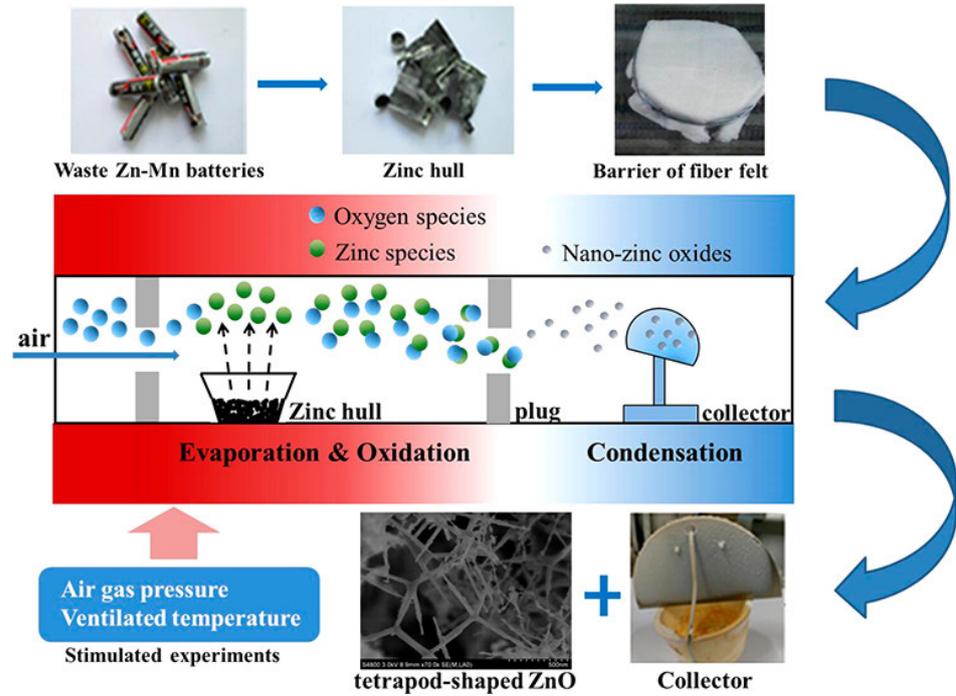


Figure 9. The schematic illustration of the ZnO recycling process from Zn-Mn batteries by high-temperature evaporation–separation and oxygen control oxidation method [124].

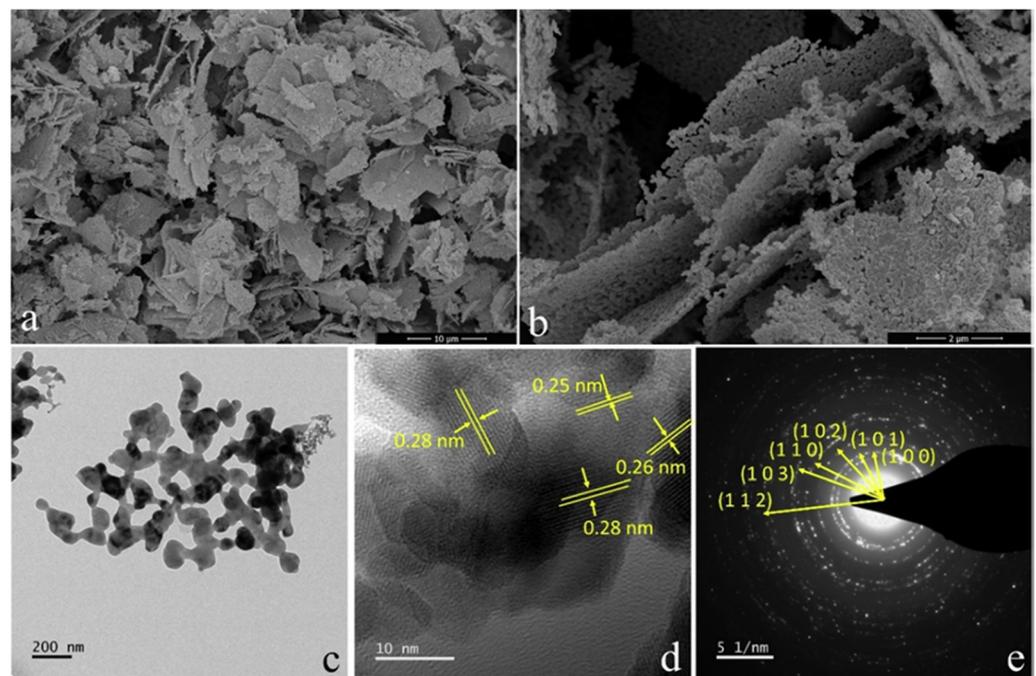


Figure 10. Microstructure of porous ZnO nano-sheets: (a) SEM; (b) SEM with high magnification; (c) TEM; (d) HRTEM; and (e) SAED patterns [126].

Finally, the photocatalytic performance of these Zn-C batteries-derived porous ZnO nano-sheets confirmed that they are a promising candidate in the photodegradation application, especially towards organic pollutants such as MB in industrial wastewater.

Obviously, the recycling of spent domestic batteries is of substantial environmental significance. In this regard, Deep et al. [40] proposed a facile chemical procedure to recycle the electrode waste of spent alkaline Zn-MnO₂ batteries to produce high-purity ZnO NPs through a one-pot leaching–combustion process. The produced ZnO NPs, having high commercial value and fluorescent nature, are highly qualified and interesting for photocatalytic, sensors, biology, and solar cell applications. Additionally, the separated pure MnO₂ product can be re-utilized in various applications [56]. The used one-pot leaching–combustion process is very advantageous due to its single-step process without any need to perform a multiple-processing route (e.g., separate leaching, extraction, and combustion steps). In addition, it has a simple route, i.e., processing in moderately concentrated chemicals at moderate temperatures. The flowchart of the used process in the investigation by Deep et al. [40] is shown in Figure 11. Firstly, the spent batteries were manually dismantled to extract their electrode material, and following the acid digestion process, the mixture powder was attained, and was comprised of Zn, Mn, Fe, Ni, Cd, and Cu. Subsequently, the leaching process was performed in HCl, Cyanex, and hexane solution at 250 °C for 30 min. The maximum extraction values were reported for 1.2 mol/L HCl in which Zn(II) had 98% extraction efficiency while Fe(III), Cd(II), Mn(II), and Ni(II), respectively, had ~30, 47, 0.5% extraction efficiencies. Then, the organic phase was collected by centrifugation, by the addition of 70% methanol, the dissolved ZnO-Cyanex 923 complex with ZnO nanoparticles was precipitated. Finally, the resulting product was repeatedly washed in methanol solution and then resuspended in dimethylformamide [40]. The valuable recovered ZnO NPs which were approximately 5 nm in diameter, when irradiated by UV radiation, showed fluorescent properties (emission peak at 400 nm) with applications in photocatalytic reactions and solar cells. In this study and in order to fabricate pure metal oxides, the ethanolic precipitation was used to prevent the high-temperature combustion step since this leads to the production of sintered metal oxides with a blackened appearance. The utilization of the ethanolic precipitation strategy leads to the high-quality recovery and generation of nano-sized white colored products that have a high commercial value and fluorescent nature with applications in bioengineering, sensors, and solar cells. These nano-size MnO₂ products are free of any impurities and are easy to re-utilize in various fields [40].

ZnO/CuO nanocomposites can be attained from recycling PCBs; accordingly, Nayak et al. [127] produced ZnO/CuO nanocomposites through acidic leaching. Then, the resultant metal salts were further processed by alkaline hydrothermal treatment. The main advantage of this hydrothermal treatment relates to supercritical water preventing the utilization of toxic organic solvents [128], making it among the ideal methods for green industry, which guarantees the preservation of environmental resources by the utilization of nontoxic supercritical solvents. For instance, Li and Xu [129] reached a 99.80% metal recovery rate by the utilization of supercritical water (as a green and environmentally friendly technology) under external-catalyst-free conditions to recover metals from the waste memory module. Despite the environmental benefits of this method, the supercritical water oxidation technique has some limitations which prevent its vast utilization and industrialization, including technical issues due to salt precipitation and reactor corrosion, large water consumption, using organic acids and other toxic materials, etc. The PCB e-wastes were successfully leached with HNO₃ solution following the alkaline hydrothermal treatment of the leachate salt solution in two conditions with biodegradable polymer stabilizer polyvinyl pyrrolidone (PVP) and without PVP [127]. This process led to the formation of ZnO/CuO nanocomposites with partial core–shell and p-n junction in which the fine ZnO nanostructures had precipitated on the CuO core nanoparticles. The resulting photocatalyst exhibited efficient methyl orange (MO) degradation under the irradiation

of visible light and the presence of H_2O_2 . These ZnO/CuO nanocomposites are proper photo-Fenton catalysts, especially for organic pollutant degradation [127].

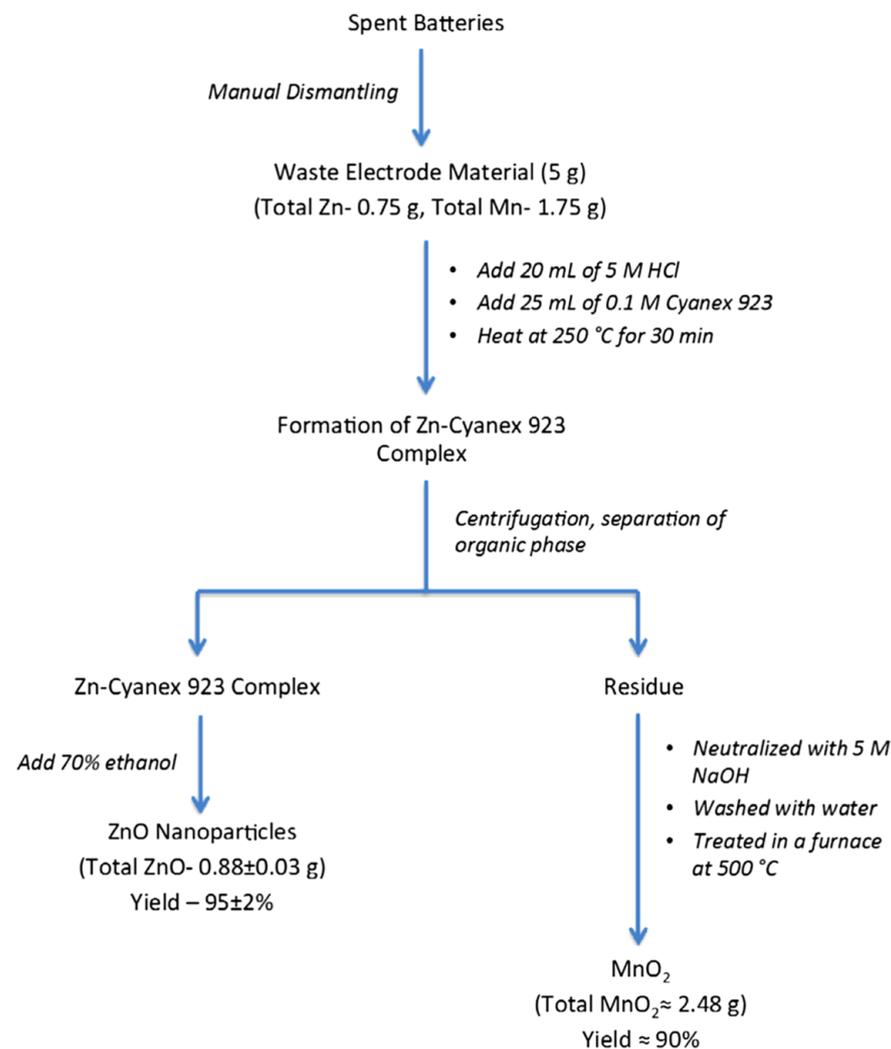


Figure 11. The processing flowchart regarding the recycling of the electrode waste of spent alkaline Zn-MnO₂ batteries to produce high-purity ZnO NPs [40].

3.2.3. Sulfide-Based Materials

Sulfides are also regarded as suitable photocatalysts, as—in this regard metal—sulfide-based photocatalysts manifested distinguished photocatalytic properties and recently have become of great interest to the scientific community [130]. Among the beneficial aspects of sulfides in the photocatalysis process, they also have some drawbacks since they are easily photocorroded in oxidizing conditions, have a high inclination to photoelectron–hole recombination and low photocatalytic efficiency and stability, demonstrate low quantum efficiency with the unsaturated active sites, etc. [131].

The morphology and mechanism of one typical metal sulfide-based photocatalyst for H_2 production is illustrated in Figure 12 in which Ag_2S -coupled ZnO@ZnS core–shell nanorods act as an immobilized hierarchical photocatalyst [132]. In this photocatalyst, the production of Ag_2S on ZnO@ZnS nanorods facilitates the photoexcited electron/hole transfer from ZnS to Ag_2S or the migration to the conductive wire mesh substrate. Various metal sulfide-based compositions can exhibit photocatalytic properties, especially the transition-metal sulfides such as CdS or ZnS. In addition, WS_2 , Cu_2S , In_2S_3 , MoS_2 , and CdS, and even some more complex structures and ternary systems, including CdIn_2S_4 , CdLa_2S_4 , and ZnIn_2S_4 have a favorable photocatalytic performance [133]. For recycling the

sulfide-based materials, several processes can be done, such as flotation and a variety of physical-mechanical separation, chemical modification methods, and extraction through supercritical H₂O or CO₂ following further required purification steps [134].

It was reported that some microorganisms have the potential and tendency to extract metals from their sulfide and iron-containing ores and mineral concentrates [135]. In this regard, iron and sulfide are microbially oxidized to generate sulfuric and ferric ions along with sulfuric acid, as these chemicals finally convert the insoluble sulfides of metals such as Cu, Ni, and Zn into a soluble sort of metal sulfates that can subsequently be simply recycled from the solution. For example, Au can be extracted from e-waste by cyanogenic-bacteria (*Chromobacterium violaceum* and *Pseudomonas fluorescens*) [136] in which the pretreatment and bio-oxidation of e-wastes by *A. ferrooxidans* specifically leads to separating and removing the Cu content whilst leaving Au residues behind [136]. The utilization of various microorganisms is significantly imperative in metal recovery especially in the case of metal sulfide-based materials. As Cu, Zn, Au, and Ag, etc., can be successfully recovered from their sulfide ores through microbial leaching, Suzuki et al. [137] reported that mineral solubilization can be attained both by ‘direct (contact) leaching’ using bacteria and ‘indirect leaching’ by ferric ion (Fe³⁺) that is regenerated from ferrous ion (Fe²⁺) via bacterial oxidation.

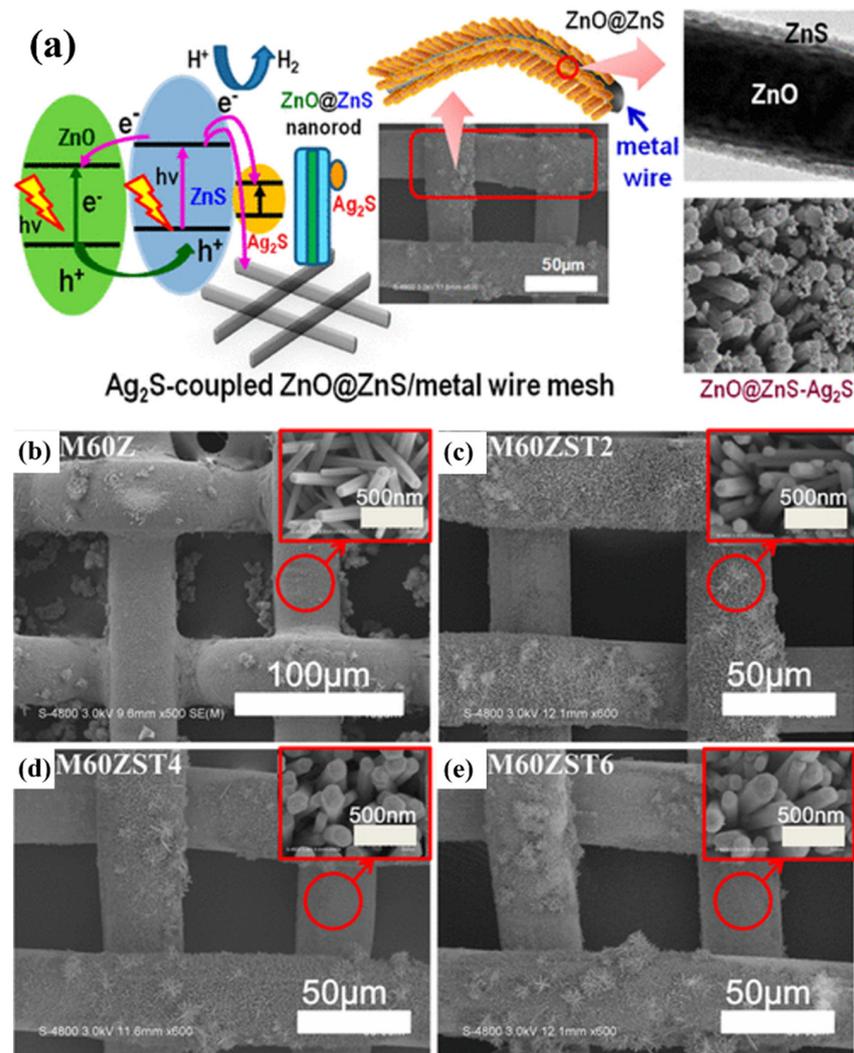


Figure 12. (a) The morphology and a related mechanism of the metal sulfide-based photocatalysts for H₂ production with Ag₂S-coupled ZnO@ZnS core–shell nanorods and FESEM images of (b) ZnO nanorods decorated stainless steel wire mesh, and ZnO@ZnS core–shell nanorods decorated stainless steel wire mesh with various sulfidation times (c) M60ZST2, (d) M60ZST4, and (e) M60ZST6 [132].

3.2.4. Ferrite-Based Materials

Magnetic photocatalyst materials have attracted much attention since they can facilitate the separation of a photocatalyst from treated water using an external magnetic field. Additionally, these magnetic NPs, including ferrite-based materials, can be easily coupled with various photocatalysts to induce magnetic behavior [138,139]. In addition, magnetic NPs can exhibit favorable visible light absorption and photocatalytic properties leading to improved overall pollutant degradation performance [140–142]. Magnetic ferrite is widely utilized in many fields due to its numerous advantages, including exceptional magnetic properties, substantial electrical resistance, chemical stability, mechanical rigidity, and low cost. Despite these advantages, ferrite-based photocatalysts have some drawbacks that should be considered, such as agglomeration issues, being unfavorable for photocorrosion, a high electron–hole recombination rate, and insufficient photocatalytic activity [143].

For the first time, Xi et al. [144] fabricated Zn–Mn magnetic ferrite NPs from dry Zn–MnO₂ waste batteries, a process which they concluded can be influenced by pH, temperature, and calcination processes. Morais and his co-workers [145] recovered a magnetic manganese ferrite (MnFe₂O₄) photocatalyst from spent Zn–MnO₂ batteries for water remediation. The MnFe₂O₄ catalyst was successfully synthesized and recycled from manganese solution by leaching the cathode material of waste Zn–MnO₂ batteries in 0.5 mol/L nitric acid and 30% (v/v) H₂O₂ solution at 80 °C, which was then followed by reacting with ferric chloride and calcination. The resultant magnetic MnFe₂O₄ photocatalyst exhibited an excellent performance toward the heterogeneous photo-Fenton photodegradation of methylene blue dye [145]. In another investigation, Mn–Zn soft magnetic ferrite powders were successfully synthesized from waste Zn–Mn dry batteries by simultaneous leaching, purification, and co-precipitation processing [146]. In addition, Mylarappa et al. [147] recovered Mn–Zn ferrite NPs from waste alkaline Zn–C batteries, and they used the acid dissolution and ferrite process and then decorated the resulting Mn–Zn ferrite NPs on rGO through the solvothermal method. These Mn–Zn ferrite NPs decorated with rGO exhibited an excellent photocatalytic activity under UV light compared to the bare Mn–Zn ferrite NPs. The nano-crystalline Mn–Zn ferrites and rGO/Mn–Zn ferrite showed average crystalline sizes between 27 and 19 nm. The superior photocatalytic activity of rGO/Mn–Zn ferrite NPs was majorly related to its finer size, oxygen vacancies, and efficient charge separation performance [147]. This rGO/Mn–Zn ferrite NPs can effectively photo-decompose an acid orange 88 dye compound in water [147].

3.2.5. Indium Tin Oxide Materials

Indium tin oxide (ITO) thin-film electrodes are photocatalytically active and can be used in the photocatalysis process to degrade different dyes and H₂ production; for instance, nanostructured ITO electrodes can successfully degrade an azo dye [148]. The ITO as a degenerate n-type semiconductor has a wide bandgap and manifests excellent electrical conductivity and can transmit visible light [149]. The ITO thin films have wide applications in transistors, radio-electronic, spintronic, solar cell, displays, organic light-emitting diodes, and other electro-optical devices [150,151], but unfortunately, their photoelectrochemical and photocatalytic properties are not fully understood and investigated. ITO is extensively used in the fabrication of touch displays of smartphones, tablets, and liquid-crystal display panels (LCD) [152]. Due to the limited world reserves of indium and its scarcity on earth, it only comprises approximately one-sixth of gold reserves; it is of vital importance to extract and recycle very expensive indium (In) from the wastes of LCD devices [153].

The existence of a high content of indium in an ITO film of waste LCD makes it a potential secondary source of indium [154]. During the recovery of In from LCD panels, special consideration should be paid to the presence of harmful and toxic elements such as liquid crystals and mercury. Generally, the recovery of In from waste LCD panels is performed by an aqueous hydrometallurgical approach. Li et al. [155] used a combined recycling technology by dismantling and chemical treatment to recover indium from waste LCDs. Their proposed method includes three main steps: (i) thermal shock processing to

separate an LCD polarizing film; (ii) ultrasonic cleaning to remove liquid crystals between the glass substrate; and (iii) dissolution processing to recover indium metal from glass [155]. In another study, Inoue et al. [152] selectively recovered indium(III) from waste flat panel displays (FPDs) through the hydrometallurgical recovery process by the utilization of porous resins impregnated with Cyanex 923 and Aliquat 336. Additionally, Hsieh and his co-worker [156] recycled indium through an economic method using hydrometallurgical and hot immersion processes. They utilized a displacement method as one of the hydrometallurgical processes to recover indium metal from ITO waste liquid, and subsequently, a slag-making process was performed during hot immersion to refine the sponge indium up to 99% [156]. Indium can also be recovered by sub-critical water, chlorination, and vacuum carbon reduction. Park et al. [157] used a chlorination method to recycle indium from In_2O_3 and liquid crystal display powder by a chloride volatilization process. Additionally, vacuum pyrolysis was used to produce indium chloride and recover indium. Furthermore, Zhang et al. [158] used an environmentally friendly method to recover indium from the waste liquid crystal display (LCDs) panels using an integrated and multi-step process. Initially, a mechanical stripping separation method was applied to the waste material and the enriched liquid crystals and indium compound was produced. Afterward, through a series of pyrolysis separation, vacuum chlorinated, and substitution reaction methods, the indium content was increased from 0.02 wt.% in waste LCDs to 36 wt.% in the final product [158], Figure 13 shows the schematic of this process.

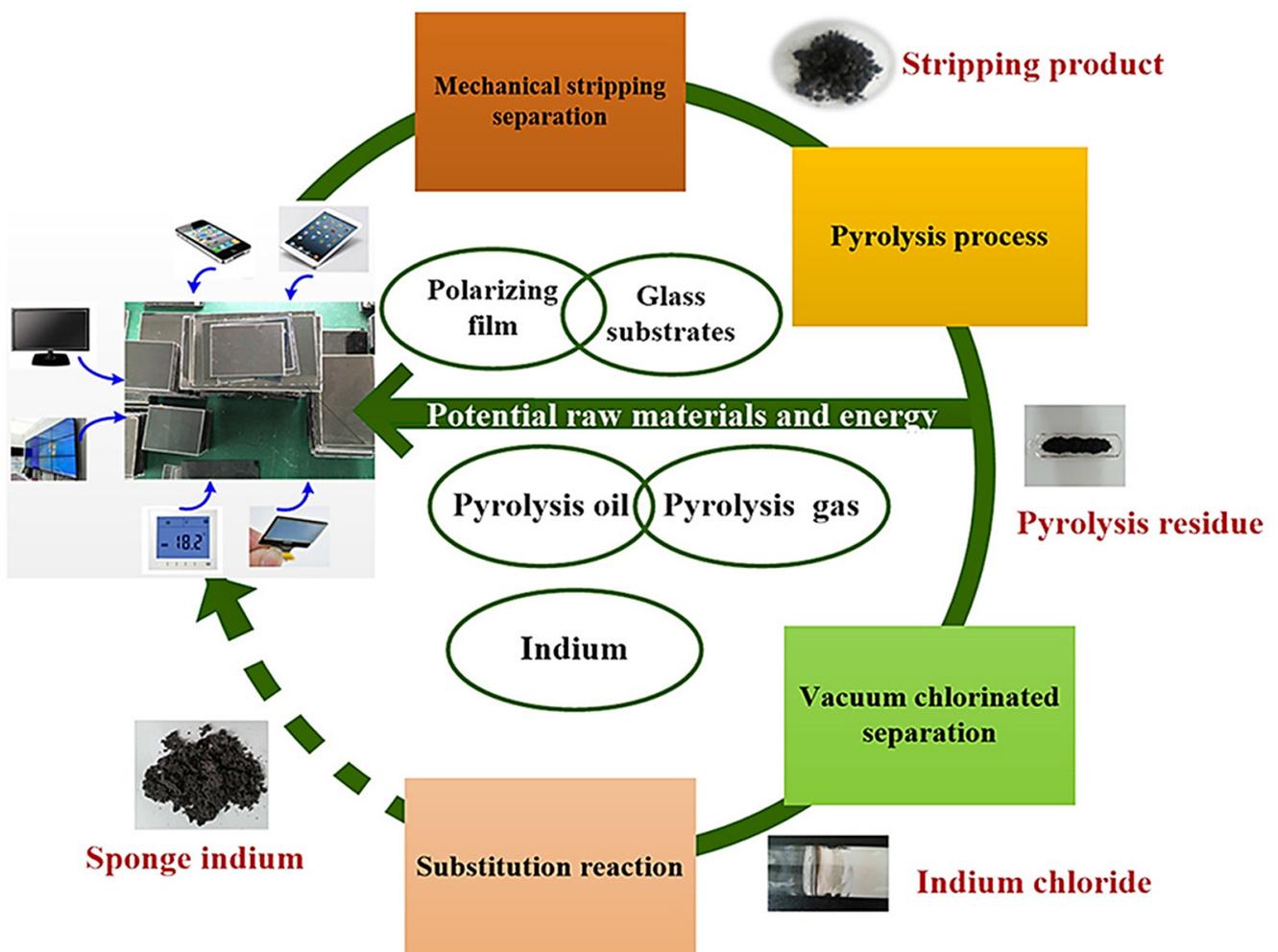


Figure 13. A schematic showing the multi-step process to recover indium from the waste liquid crystal display (LCDs) panels [158].

3.2.6. Other Photocatalytic Materials from E-Waste

Along with many applications of carbon quantum dots (CQDs) due to their nontoxic and biocompatible nature in the biomedical field (bio-imaging, drug delivery, bactericidal activity, gene delivery, and cancer therapy) [159], they are also utilized in solar energy conversion, photosensors, light-emitting diodes, chemical sensing, and photocatalysis. The CQDs' application in photocatalysis is highly interesting due to their excellent light-harvesting capability and substantial photo-induced electron transferability [160]. CQDs are an important class of carbon nanomaterial photocatalysts which have many applications in pollutant degradation, solar devices, and photo/electrochemical water splitting due to their attractive advantages including efficient light-harvesting capability, controllable photoluminescence, exceptional up-converted photoluminescence, and excellent photoinduced electron transfer which finds their way in photocatalysis systems [161]. Despite the high separation rate of electron-hole pairs, favorable photodegradation efficiency, economic nature, low toxicity, chemical inertness, superiority in water solubility, biocompatibility, fluorescence emissions, high resistance to photobleaching, facile functionalization, and synthesis, CQDs also have some limitations that should be considered and solved. For instance, the charge separation efficiency should be enhanced along with the need to improve the spectral responsive range. Additionally, CQDs have demonstrated some issues regarding the flow direction of photogenerated charge carriers and limited functionalities that should be improved [160].

CQDs can be processed and recycled from e-waste through acidic hydrolysis, hydrothermal and electrochemical oxidation, and microwave-assisted treatments [162]. Devi et al. [163] proposed an efficient method by the utilization of carbon black extraction and pyrolysis methods to recycle carbon species, particularly carbon black from discharged batteries and transformed them into zero-dimensional carbon nanomaterial CQDs with photocatalytic applications.

The e-waste toner powders can be turned into magnetic $g\text{-C}_3\text{N}_4\text{-Fe}_2\text{O}_3$ photocatalyst material through the calcination method. Barber et al. [164] reported the successful production of the $g\text{-C}_3\text{N}_4\text{-Fe}_2\text{O}_3$ photocatalyst from e-waste toner powders; firstly, Fe_3O_4 was transformed into useful magnetic Fe_2O_3 using direct calcination at $600\text{ }^\circ\text{C}$; then, e-waste-derived Fe_3O_4 by a simple one-step calcination process turned into $g\text{-C}_3\text{N}_4\text{-Fe}_2\text{O}_3$. This $g\text{-C}_3\text{N}_4\text{-Fe}_2\text{O}_3$ photocatalyst material manifested a proper photocatalytic behavior and a promising degradation efficiency toward methyl orange (MO) and textile effluents (TE) under sunlight irradiation [164]. This material has a far better photocatalytic performance than the Fe_2O_3 and $g\text{-C}_3\text{N}_4$. Figure 14 shows the schematic of the process steps. At first, residual toner powders were collected from the waste print cartridge which were then calcined at $600\text{ }^\circ\text{C}$ for 2 h in air to generate crystalline Fe_2O_3 . Subsequently, the well-known polycondensation method was used to synthesize $g\text{-C}_3\text{N}_4$ and $g\text{-C}_3\text{N}_4\text{-Fe}_2\text{O}_3$ [165,166]. In this regard, thiourea was placed into an alumina crucible with a cover and heated at $450\text{ }^\circ\text{C}$ in a muffle furnace for 2 h. The produced yellow color material was ground into a fine powder and designated as $g\text{-C}_3\text{N}_4$. Then, the prepared Fe_2O_3 and thiourea were ground together and calcined at $450\text{ }^\circ\text{C}$ in a muffle furnace for 2 h. Finally, the developed product was washed with distilled water and dried in an oven at $80\text{ }^\circ\text{C}$, eventually, the resulting product was designated as $g\text{-C}_3\text{N}_4\text{-Fe}_2\text{O}_3$ [164]. The produced $g\text{-C}_3\text{N}_4\text{-Fe}_2\text{O}_3$ photocatalyst demonstrated 97% photocatalytic activity under sunlight and within 60 min degradation time toward the textile effluents pollutant.

The $\text{V}_2\text{O}_5/\text{Zn}$ -ferrite photocatalyst can be recycled from vanadium nitrate which is produced from the metallurgical treatment of vanadium redox battery. As a semiconductor metal oxide, V_2O_5 has a low bandgap energy of 2.2 eV that facilitates the electron-hole recombination under light irradiation [167]. Mohan et al. [168] generated zinc-ferrite/ V_2O_5 (ZfV) magnetic nanocomposite photocatalysts from e-waste (vanadium batteries) for the photocatalytic degradation of BTEX isomers in an aqueous solution. ZfV magnetic nanocomposite was fabricated by solvothermal procedure by the utilization of V_2O_5 (recycled from the treated E-waste), and zinc ferrite (synthesized through chemical

co-precipitation method) [168]. It was observed that the efficiency of the photocatalyst is dependent on many variables (pH, additives, etc.) and the maximum efficiency was attained under conditions of 50 mg/L initial concentration of BTEX, 0.50 g/L catalyst loading, and a pH of 3. The degradation efficiency at the end of 90 min was improved up to 98% with H_2O_2 addition, while the addition of NaCl , Na_2CO_3 , NaNO_3 , and Na_2SO_4 considerably decreased the degradation values to 60%, 65%, 80%, and 75%, respectively—a phenomenon related to the hydroxyl scavenging properties. Additionally, it was shown that the degradation efficiency could be increased up to 98% by the addition of H_2O_2 while the addition of NaCl , Na_2SO_4 , NaNO_3 , and Na_2CO_3 reduced the degradation rate. Eventually, it was confirmed that zinc-ferrite/ V_2O_5 (ZfV) magnetic nanocomposites could be successfully utilized for the treatment of BTEX-bearing wastewaters [168].

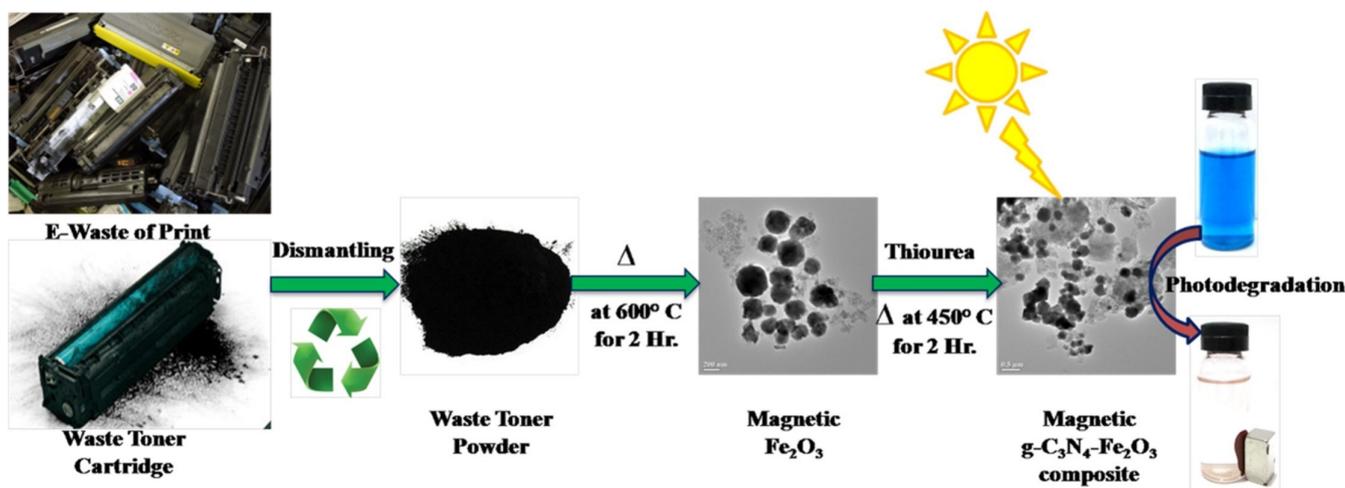


Figure 14. The schematic of the process steps for recycling magnetic $\text{g-C}_3\text{N}_4\text{-Fe}_2\text{O}_3$ from e-waste toner powders [164].

Waste printed circuit boards can be directly recovered and transformed to value-added high surface area t-SnO_2 nanoparticles (NPs) for photocatalytic MB dye degradation under UV irradiation [169]. These high-surface-area t-SnO_2 NPs which can be regarded as quantum dots (QDs) were produced by a spontaneous precipitation method from a pregnant e-waste leachate solution with a very slow kinetic rate without any need for additives. The nucleation and growth processes were taking place under equilibrium conditions and led to successful QD precipitation. In another study, Mohan et al. [170] fabricated a graphene oxide/ V_2O_5 /Pt ternary composite from e-wastes to attain anti-microbial and anti-cancer activity through visible-light-driven photocatalysis interaction. They analyzed the photocatalytic disinfection and anti-cancer activity features of the graphene oxide/ V_2O_5 /Pt (GOV-Pt(1%)) nanocomposite by *Salmonella typhimurium* as a model system [170]. With the photocatalyst produced by the solvothermal process, uniform dispersion was achieved by sonication in methanol for 30 min at room temperature. Then, V_2O_5 was produced as in Harshavardhan et al. [171] and mixed in GO suspension, autoclaved, and heated at 120 °C for 8 h, and finally washed, filtered, and vacuum dried at 90 °C. The platinum doping of GOV was assessed by platinum(II) chloride (PtCl_2) and GOV addition into double distilled water and vigorous stirring until it became dry. Then, the dried mixture was scraped, reduced to hydrogen gas atmosphere at 450 °C, and entitled GOV-Pt(1%) and GOV-Pt(2%), as represented in Figure 15 [170]. GOV-Pt(1%) demonstrated high antibacterial efficiencies of up to 100% at 30 min for most of the microbial pollutants and 99% at 24 h for apoptosis in the B16F10 cells. The resulting graphene oxide/ V_2O_5 /Pt ternary photocatalytic composite manifested an excellent disinfection rate in real effluents, which also efficiently prevented the growth of $\text{B}_{16}\text{F}_{10}$ cancerogenic melanoma cells.

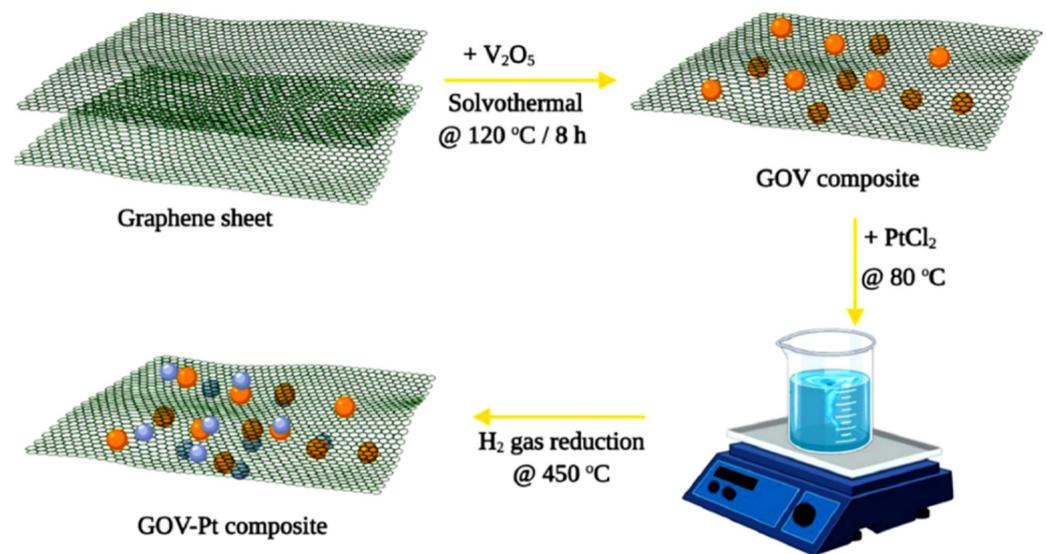


Figure 15. The schematic illustration of a graphene oxide/ V_2O_5 /Pt ternary composite photocatalyst synthesis [170].

E-waste is also an excellent source of silica and can be used to synthesize photocatalytic material: Liou et al. [172] used a packaging resin ash (PRA) to produce the silica-supported TiO_2 photocatalyst. In this regard, they directly synthesized TiO_2 NPs which were loaded on MCM-48 e-waste-derived material from the alkali-extracted electronic packaging resin ash as a source of sodium silicate precursor. TiO_2 NPs were impregnated on PRA-MCM-48 supports using a sol-gel technique to produce TiO_2 -modified mesoporous silica. The utilization of the MCM-48 support enhanced the TiO_2 photo-efficiency of the catalyst by inhibiting the aggregation of TiO_2 particles. The optimum condition for higher photocatalytic activity was reported for the TiO_2 /PRA-MCM-48 molar ratio of 30% with $700\text{ }^\circ\text{C}$ heat-treatment temperature. This photocatalyst is effective to degrade methylene blue dye and has an excellent photocatalytic activity [172].

Cao et al. [173] proposed a new method to recycle waste capacitors into an Nb-Pb-co-doped and Ag-Pd-Sn-Ni-loaded $BaTiO_3$ photocatalyst, for which they used a simple ball milling method instead of traditional acid leaching methods. In addition, to further enhance their photocatalytic performance, they added polyaniline (PANI) during the ball milling. Eventually, the produced photocatalyst has a specific surface area of $21.11\text{--}40.27\text{ m}^2/\text{g}$ and a particle size of $100\text{--}500\text{ nm}$. The photocatalytic hydrogen production rate of the optimized Nb-Pb-co-doped and Ag-Pd-Sn-Ni loaded $BaTiO_3$ photocatalyst with PANI is considerably high, and it is 3.72 times superior ($686.4\text{ }\mu\text{mg}^{-1}\text{h}^{-1}$) to that of the Nb-Pb-co-doped and Ag-Pd-Sn-Ni loaded $BaTiO_3$ photocatalyst ($210.5\text{ }\mu\text{mg}^{-1}\text{h}^{-1}$) [173]. In addition, this photocatalyst has excellent photocatalytic stability and can be recovered through magnetic separation due to the Ni composition. These superior features were attributed to the PANI addition that significantly enhanced the visible light absorption and charge separation of the photocatalyst. Figure 16a shows the waste multilayer ceramic capacitors (including dielectric material $BaTiO_3$, internal electrode Ag-Pd/Ni, end electrode Ag-Ni/Sn), disassembling from the circuit board and corresponding content elements. Additionally, Figure 16b illustrates the processing diagram for the production of the Nb-Pb-co-doped and Ag-Pd-Sn-Ni-loaded $BaTiO_3$ photocatalyst with PANI [173].

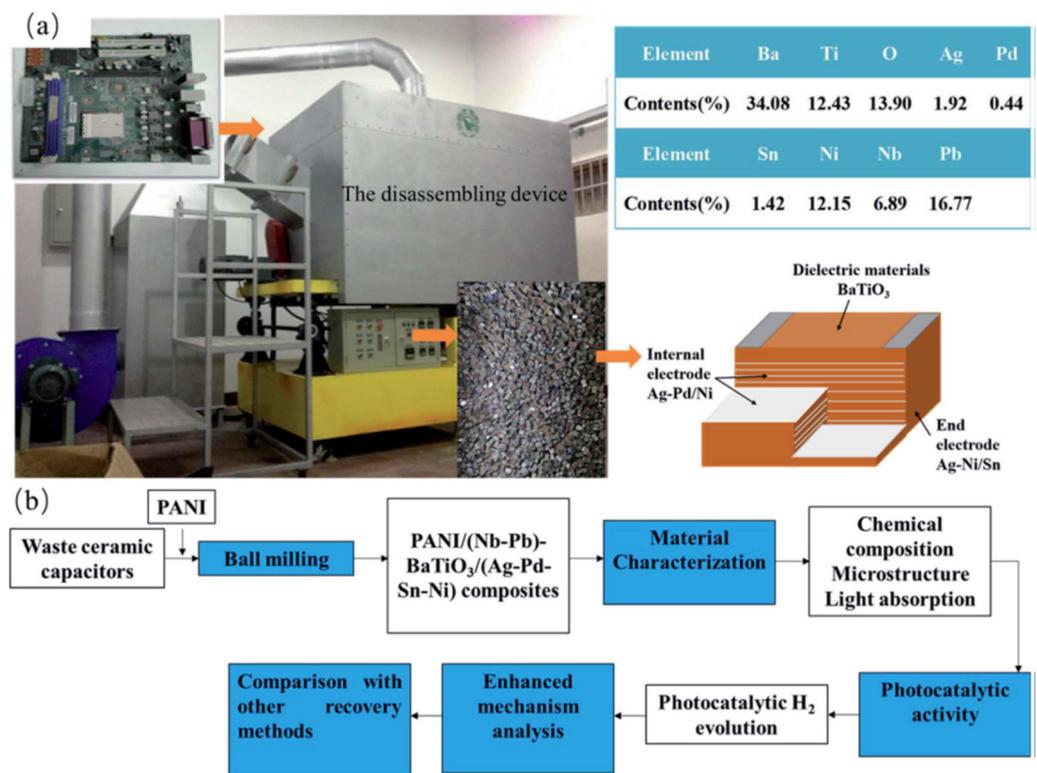


Figure 16. (a) The waste multilayer ceramic capacitors (including dielectric material BaTiO₃, internal electrode Ag-Pd/Ni, and end electrode Ag-Ni/Sn), disassembling from the circuit board and corresponding content elements and (b) the processing diagram for production of Nb-Pb-co-doped and Ag-Pd-Sn-Ni loaded BaTiO₃ photocatalyst with PANI [173].

In addition to many metals, Pb particles can also recover and recycle from waste printed circuit boards (WPCBs), and Zhan and Xu [49] separate Pb from the solder mixed and copper-rich compounds of crushed WPCBs through evaporation and condensation methods. A flowchart of Pb recycling from WPCBs is shown in Figure 17, firstly after dismantling and removing electronic elements from WPCB, and the pulverizing process was performed in two steps, namely coarse crushing and fine-pulverizing. Subsequently, through an electrostatic separator, the metals and nonmetals were separated. The copper-rich compound was recovered via vacuum metallurgy separation (VMS) under 0.1–1 Pa pressure at 1123 K heating for 90 min. Then, the separated Pb particles from the copper-rich compound were condensed as Pb prills. The sieving procedure helps to categorize the output materials into two groups of Cu particles and Cu-Sn alloys. Different processing temperatures lead to various Pb extraction efficiencies from 3% (solder) at 600 °C up to ~98% at 850 °C (Cu + solder). This method can play a significant role in applications where Pb contamination must be avoided and it can also be utilized to separate other toxic heavy metals such as Cd and Hg [49]. Waste nickel–cadmium (Ni-Cd) batteries are also considered as a source of metals, and in this regard, Huang et al. [68] utilized vacuum metallurgy separation (VMS) and magnetic separation (MS) methods to recover Cd and some other ferromagnetic metals through an efficient and eco-friendly method. The reported optimum conditions were a temperature of 750 °C, the addition of 1 wt. %, carbon powder, and a heating time of 1.5 h which led to 99.2 wt. % Cd extraction with 99.98% purity.

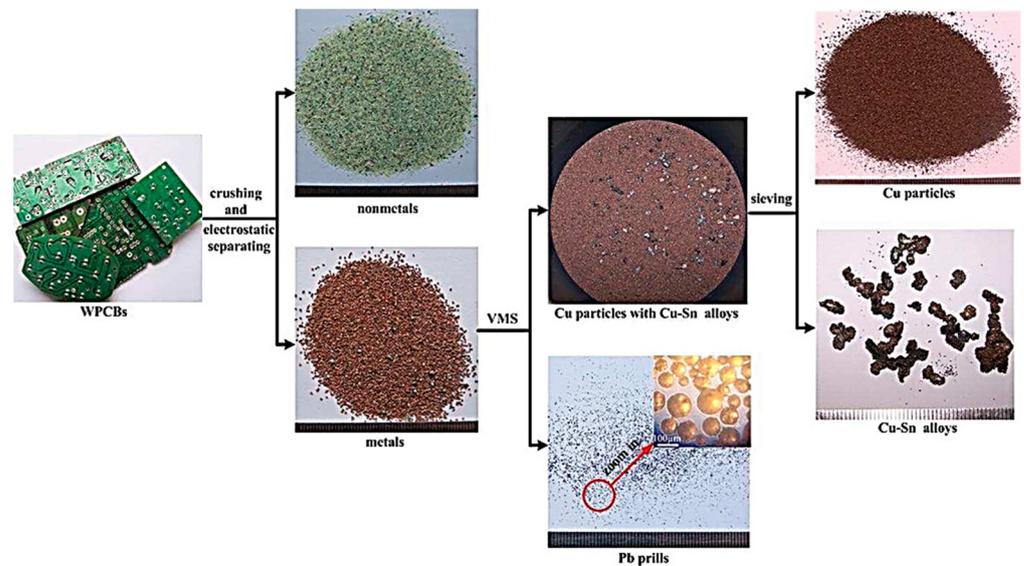


Figure 17. A flowchart representing Pb recycling from waste printed circuit boards (WPCBs) [49].

3.3. Insights and Critiques

Despite growing concerns about the adverse environmental aspects of e-waste, considerable research studies on safer and effective management strategies for e-waste have been advancing at a rapid rate. These studies and reports have mainly focused on management strategies, utilization prospects, e-waste transformation, etc., while limited studies have focused on improving the techniques for utilizing e-waste as a source for photocatalytic applications. The most crucial challenge in the field of photocatalytic materials produced from e-waste is to improve the techniques to fully satisfy the requirements, such as a low processing cost, high efficiency rates, simplicity, no need for high temperatures and time, strong acids, less water and solutions consumption, nontoxicity, and being environmentally friendly. In this regard, numerous procedures have been introduced and implemented by academia and industry, each of which has its own advantages and limitations which determine the potential applications. Within pyrometallurgical methods, the most-used method in e-waste recycling, high temperatures (approximately 1000 °C) are needed, leading to very fast extraction processes. This can successfully be used for a large-scale application with complex heterogeneous mixtures. Unfortunately, the efficiency is low, and it is not capable of selective recovery. Improving efficiency by these methods requires the repetition of the procedure in some subsequent steps leading to a very high energy consumption. Another significant weakness of pyrometallurgy methods is that they are not environmentally friendly at all and usually lead to a high amount of pollutant emissions, mostly carbon dioxide and sulfides [174,175].

In hydrometallurgical processes, redox chemical reactions are used in aqueous or organic liquid solutions in which metals have previously undergone leaching processes and have been oxidized from their matrices before being transformed into soluble salts. Hydrometallurgical processes use low temperatures and high pressures (up to 5000 pascals) and are very flexible due to the large number of reactions in the metal separation from dissolved salts. In comparison to pyrometallurgical methods, hydrometallurgy techniques have slow kinetics and limited yields, and they are highly sensitive to slight variation in environmental conditions. These methods need high amounts of energy and unfortunately produce a considerable amount of both solid waste and wastewater, but they usually have higher recovery rates and lead to higher purities than pyrometallurgy methods. These methods are not environmentally friendly and use strong acidic and alkali solutions [176]. Biohydrometallurgy methods are very similar to hydrometallurgical processes, and the leached metals by the production of salts facilitate the recovery procedure. The main difference is the utilization of various microorganisms to conduct metabolic reactions,

increasing the sensitivity of extraction and reducing the energy costs, toxic gas emission, and wastewater. Unfortunately, the reaction kinetics of biohydrometallurgical methods are very slow while they are very environmentally friendly [177].

Considering these facts, the necessity to improve methods is obvious for achieving high-throughput technologies in the future and still, there is a considerable number of challenges. Li et al. [178] investigated the recovery of precious metals and rare earth elements from e-waste through different methods and performed the pyrometallurgy method in smelting furnaces to recycle precious metals and Cu with up to 95% efficiency rates, but it could not recover other metals. The electrochemical recovery showed the lowest environmental impacts compared to the hydrometallurgy and pyrometallurgy methods. In another study, Ding et al. [179] studied the recovery of precious metals from e-waste and spent catalysts using chlorination leaching (hydrometallurgy) and demonstrated that, despite the economic nature of the process and its low toxicity, it unfortunately leads to the emission of Cl_2 as waste pollution. It was also reported that iodation leaching leads to low toxicity and high recovery rates while it has a high cost and leads to water pollution [179]. Additionally, halide leaching methods are difficult to implement because of their severe corrosive and oxidizing conditions. On the other hand, the extraction supercritical fluids with high recovery rates toward Pt, Pd, and Rh led to considerable waste emissions, including waste oil and waste gas pollution, and the size reduction by mechanical methods resulted in a 20% loss of precious metals. Masilela and Ndlovu [180] tried to recycle Ag and Au from the chloride aqua regia leach liquors of PCBs and demonstrated that the utilized liquid–liquid and solid–phase reactions had high selectivity and superb extraction efficiency (95% Ag, 97% Au, and 99% Cu); however, using these ionic liquids has disadvantages due to their volatility, inflammability, toxicity, and non-recyclability. In another study, despite its high leaching efficiency, $\text{HCl}+$ oxidant leaching led to the generation of chlorine gas which was toxic and corrosive in nature [178]. In the case of electrochemical methods, they present high energy efficiency, selectivity, low environmental impact, and minimal chemical usage, but these need multiple processing steps which make it more difficult and costly [181]. Finally, despite their various benefits, bioleaching and biotechnological processes have numerous challenges, including low extraction efficiency, the needs for multistep recycling strategies, and high time consumption [74,182]. For instance, the metal bioleaching of e-waste by moderately thermophilic acidophilic bacteria leads to recovery efficiencies of 89% Cu (76 mg/g), 81% Ni (16.2 mg/g), and 83% Zn (66.4 mg/g) with remnants of Pb and Sn [88]. The presented information indicated that the methods must be improved to solve the so-called limitations and novel techniques should be designed to solve the issues and improve the characteristics of the process with a special focus on the environmental impacts.

4. Conclusions, Recommendations, and Future Prospects

Considering the ever-increasing trend of e-wastes due to the technological development of the world, the reuse of these types of wastes, such as printed circuit boards, and batteries, is crucial, specifically as production and metal refining costs from natural ores are generally high. In addition, due to global warming and environmental issues, the utilization of green technologies that are eco-friendly in nature is of substantial importance. Because of these reasons, e-waste recycling with photocatalytic applications will be a very imperative field in the near future from scientific, economic, and environmental aspects. This review discusses e-waste-derived photocatalytic materials as an attractive green technology. In this regard, the authors sought to highlight all aspects of e-waste-derived photocatalytic materials from synthesis, mechanism, and technologies to challenges, applications, and performance. Hence, this paper described various e-waste-derived photocatalytic materials, synthesis procedures, and applications, as well as some of the e-waste-derived materials that were previously investigated such as TiO_2 , ZnO , and indium tin oxide, and a variety of sulfide- and ferrite-based photocatalytic materials were also reviewed.

In general, e-waste recovery aims to take today's waste and economically transform it into tomorrow's eco-friendly, conflict-free, sustainable polymetallic secondary resources (i.e., urban mining). Unfortunately, the large-scale fabrication of e-waste-based photocatalytic materials is not well established. It is also evident that traditional technologies cannot cover all the requirements of future and modern technologies, particularly due to environmental issues, high costs, and low efficiency. Accordingly, it is clear that new schemes should be proposed and developed to meet the so-called criteria, leading to high-throughput recycling and recovering technologies from e-wastes in order to reach proper photocatalytic materials.

The presented overview on the e-waste recycling for photocatalytic applications provides some evidences that numerous methods can be utilized for this aim, mainly hydrometallurgical and pyrometallurgical ones. Despite the high effectiveness of these methods with high recovery rates (ranging between 80 and 100), many challenges remain, such as the need to use strong and toxic acids, high energy consumption issues, the limitation of fully selective extraction, the simultaneous retrieval of several elements, the existence of toxic and contaminating residue, and the need for disposing of a high amount of aqueous waste. For instance, over 24 metallic elements can be found in a single PCB [183], and up to 60 elements can be found in e-wastes [184]; hence, the selective green recovery (by the utilization of nontoxic materials and environmentally friendly techniques) of multiple elements with high efficiency will lead to considerable economic and environmental revenue. Unfortunately, usual hydrometallurgical and pyrometallurgical methods cannot be an appropriate answer to the problems and needs of the present and future situations. In this regard, it is highly recommended that new schemes, methods, and materials are designed with the utilization of high-tech equipment that will lead to high returns. Additionally, environmental issues should be considered, for example, as recent investigations have shown that the utilization of suitable microorganisms in a combination of hydrometallurgical approaches (biohydrometallurgical methods) could be very helpful in achieving this aim. Therefore, the development of biohydrometallurgical methods as a high-throughput method for multiple selective extraction is a hot topic for researchers in the field. Additionally, supercritical fluid technology, which is basically a pharmaceutical technique, has recently been proposed for the extraction of metals from e-waste with high efficiency and high selectivity [185]; this method is economic, available, has a rapid reaction rate, and is environmentally friendly [186,187]. Hence, the development of the new procedures based on supercritical fluid technology for e-waste-derived photocatalytic materials is highly suggested for future studies.

Considering the current literature, the priority of the utilization of pyrometallurgical- and hydrometallurgical-based procedures in the metal recovery and photocatalytic material synthesis from e-wastes is obvious, implying that the newly introduced methods still have not reached industrial levels. Therefore, other techniques should be considerably developed by considering the environmental issues and increasing efficiency, to simultaneously recover multiple materials from various types of e-wastes. Although there is a long way to go, this goal is still achievable in the future.

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