Rev Environ Sci Biotechnol (2026) 25:13
https://doi.org/10.1007/s11157-026-09764-8

REVIEW

Advanced treatment of flat panel displays through chemical and biological methods: promises for the future

Jana Sedlakova-Kadukova · Joanna Willner · Janja Trček · Vid Potočnik · Magdalena Jabłońska-Czapla · Iva Janakova

Received: 1 September 2025 / Revised: 12 January 2026 / Accepted: 14 January 2026

Abstract The growing demand for electronic devices and the consequent rise in electronic waste underscore the urgent need for sustainable management strategies, particularly for flat panel displays (FPD). This review provides a comprehensive overview of advanced FPD treatment methods that integrate chemical and biological methods, highlighting their potential to advance circular economy practices. The study identifies key target groups in FPD recycling along with their specific requirements, and offers a detailed characterization of FPD, focusing on the composition of display materials, such as indium-tin oxide (ITO) and various organic compounds. Current recycling technologies are reviewed in detail, covering both conventional pretreatment methods and emerging biotechnological solutions. Special emphasis is placed on metal dissolution through hydrometallurgical and biometallurgical processes, followed by recovery techniques employing chemical and biological methods. The paper also addresses critical analytical challenges associated in characterization and monitoring of FPD recycling processes. By integrating biological and chemical approaches, this study outlines a promising route toward more efficient, environmentally friendly, and economically viable FPD recycling, offering valuable guidance for future

J. Sedlakova-Kadukova
ALGAJAS s.r.o., Prazska 16, 04011 Kosice, Slovakia
e-mail: jana.sedlakova@algajas.com; sedlakovaj@fld.czu.cz

J. Sedlakova-Kadukova
Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Kamycka 129, Praha 6 – Suchdol, 16500 Prague, Czech Republic

J. Willner
Faculty of Materials Engineering and Industrial Digitalization, Silesian University of Technology, Ul. Krasińskiego 8, Katowice, Poland
e-mail: joanna.willner@polsl.pl

J. Trček (✉) · V. Potočnik
Department of Microbiology, Biotechnical Faculty, University of Ljubljana, 1000 Ljubljana, Slovenia
e-mail: janja.trcek@bf.uni-lj.si

V. Potočnik
e-mail: vid.potocnik.2@gmail.com

J. Trček
Department of Biology, Faculty of Natural Sciences and Mathematics, University of Maribor, 2000 Maribor, Slovenia

M. Jabłońska-Czapla
Institute of Environmental Engineering, Polish Academy of Sciences, Ul. M. Skłodowskiej-Curie 34, 41–819 Zabrze, Poland
e-mail: magdalena.czapla@ipispan.edu.pl

I. Janakova
Department of Environmental Engineering, Faculty of Mining and Geology, VSB-Technical University of Ostrava, 708 00 Ostrava, Czech Republic
e-mail: iva.janakova@vsb.cz

Published online: 09 February 2026

technological development and policy development, fully in line with circular economy principles.

Keywords E-waste recycling · Flat panel display recycling · Biotechnological methods · Indium recovery · Organic material removal

1 Introduction

In 2022, the global production capacity for Flat Panel Displays (FPD) amounted to 327 million m^2 referring to the total surface area of glass substrates (approximatelly 409,000 t), which represents an increase of more than 25% over five years (231 million m^2 in 2017) (Sherif 2025). This trend reflects the growing demand for screens in the electronics industry, from smartphones and laptops to televisions and industrial displays. During the same year, global e-waste reached a record of 62 Mt and is projected to rise to 82 Mt by 2030. FPD represent a significant share of this total, although they are not always easily distinguishable from other categories of e-waste. Nevertheless, it is estimated that discarded liquid crystal displays (LCD) screens and monitors alone generate tens of millions of tons of waste annually. Within the overall e-waste stream, about 10% (5.9 Mt) originates from used screens and monitors, and 5 Mt is a group of small information technology (IT) and telecommunication equipment (mobile phones, GPS devices, personal computers). But LCD screens are also present in small equipment such as video cameras or toys, and this group constituted the largest category of e-waste in terms of 20 Mt in 2022. It is also evaluated that only 22.3% of generated e-waste are documented as formally collected and recycled (Baldé et al. 2024).

According to the Platform for Accelerating the Circular Economy (Report, 2019), if current trends continue, global e-waste could double to 120 Mt per year by 2050. Among the various types of e-waste, monitors represent the second-largest group and are produced in vast quantities annually. Considering that worldwide organic light emitting diode (OLED) substrate production capacity reached 67.6 million m^2 in 2023, the volume of this type of waste is expected to increase further (Laricchia 2025). Focusing solely on screens, the Europe FPD market (e.g., smartphones, tablets etc.) accounted for 23% of global TV sales in 2021. This equates 213.5 million units sold, making Europe the largest TV market in the world (www.etnews.com 2022).

In addition to their large quantities, FPD are a rich source of valuable metals such as In, Ge, and Ga. In is found in displays at concentrations of approximately 250 mg/kg, what is 10–100 times higher than its concentration in natural ores (Yoo et al. 2022). The EU region is the main consumer of finished products containing In, with an estimated cumulative addition of around 500 t of In to urban waste (Ciacci et al. 2019). Future demand projections indicate substantial growth, with expected increases by 2050 relative to 2010 of 225% for In, 224% for Ga, and 2130% for Ge. Current estimates suggest that only 25% of global In demand for solar cells can be met, posing a significant challenge to the energy transition (Zheng et al. 2023).

In the EU, the total amount of electrical and electronic equipment placed on the market in 2021 was 13.5 Mt, yet only 4.9 Mt of e-waste were collected, representing just 36% of the total produced. Most of e-waste continues to be landfilled. In recycling remains a significant challenge, with less than 1% currently recovered from End-of-Life (EoL) products (Talens et al. 2018). Moreover, according to the European Chemical Society, e-waste in landfills accounts for 70% of toxic metal effluent, posing a considerable threat to environmental protection. Recent findings also suggest that metal-containing landfills may act as hotspots for the spread of antibiotic resistance genes in non-hospital environments (Lachka et al. 2023). All these data highlight the insufficient recycling rates of In and other metals from FPD, which are classified as a Critical Raw Materials (CRM) by the European Commission. As a readily available source of critical metals crucial for the European economy, FPD waste requires a comprehensive and sustainable approach to recycling. This need becomes even more pressing considering the urgent requirement to establish a closed loop for In and other metals in Europe, ensuring raw material independence.

Here we aim to summarize current practices in FPD recycling and to highlight emerging biotechnological approaches that could enhance recycling rates, improve metal recovery, and enable the production of other commercially attractive products beyond metals, such as bacterial cellulose. The application of various bacterial processes and their integration with existing technologies holds great promise for the future recovery of metals from e-waste, fully in line with circular economy principles.

The primary producers of most FPD panels are East Asian countries (the Republic of Korea, Japan, Taiwan, and China) but used FPD devices are generated worldwide. Depending on the type of FPD and the brightness intensity used, display lifespan ranges from 1 to 11 years. For example, LCD typically last around 50,000 h, or approximately 5 years, which is half the lifespan of LED displays. Mobile phones, by contrast, have a service life of only 1–3 years (Wang et al. 2021; Samsung 2025). Nevertheless, given current consumer lifestyle and the frequent replacement of electronic gadgets with newer-generation models (e.g., mobile phones, tablets), the actual lifespan of these devices is often considerably shorter.

The EU's transition to a climate-neutral economy by 2050 is accompanied by a continuous increase in the production (or import from Asian countries) of equipment components in strategic sectors. This includes placing products on the EU market, using them, and eventually decommissioning and recycling them in the following years. Despite numerous studies in recent years, a complete recycling cycle has yet to be developed for many components that contain critical metals. In addition to Li, Co, Mn, and Ni from Li-ion batteries, Nd, Dy from permanent magnets, and Ga and Te from solar panels, In is also identified as a metal for which improved recycling rates are urgently needed in the EU. Currently, most In recycling takes place in facilities that produce indium-tin oxide (ITO), primarily from spent ITO sputtering targets and In-bearing electronic scrap, resulting in a closed-loop recycling system (Zhang et al. 2015; Ober 2017; Tolcin 2017). As ITO production is heavily concentrated in Japan, China, and the Republic of Korea, together accounting for about 90% of global ITO production capacity, In recycling from EoL products within the EU is essentially non-existent (Graedel et al. 2011; Ober 2017; Frenzel et al. 2017; QUMEC 2020).

FPD pose significant challenges for recycling due to their complex composition but also offer great opportunities because of the presence of valuable materials and their recovery potential. Circular economy strategies for FPD should focus on optimizing the lifecycle of displays by reducing resource inputs, extending product lifespans, and ensuring effective EoL recovery. Circular economy activities for FPD comprise a complementary structure of initiatives, challenges, and needs that involve all stakeholder and target groups (Fig. 1). Manufacturers of FPD, consumers (end users), retailers and distributors, recycling and waste management companies, repair and refurbishment service providers, policymakers and regulators, research and development institutions, and educational organizations form a complex web of connections and dependencies within the circular model for FPD. Figure 1 illustrates the stakeholder structure in the central Europe for FPD, showing flows, gaps and stakeholders' functions. The EU's main challenge in this framework is the gaps in the FPD recycling system. One of the main limitations is the low FPD collection rates, reaching only ~ 14% in some countries (e.g., France) (Horta et al. 2020). As a result, more that over 60% of potentially valuable materials are lost because a large proportion of waste never reaches official collection points. According to Eurostat, the recycling rate for old electronics remains low, with an estimated 25–50% of Europeans keeping their old, unused devices at home. In 2017 alone households stored 800 million mobile phones, or about 70,000 t (Romagnoli et al. 2022).

Limited availability of the waste stream, combined with the dispersion and low concentration of In in FPD, and the complexity of its recovery technologies, constitutes a significant technical and economic barrier to realistic implementation. Furthermore, the EU remains heavily dependent on primary In imports. This, coupled with the lack of dedicated, scalable industrial technologies for In recovery from ITO layers, and the ambitious EU policy on critical raw materials (CRM) and the development of strategic sectors (renewable energy, electric mobility, aviation, digital technologies), indicates a gap between regulatory declarations and recycling practice. Therefore, improving the monitoring of FPD streams and developing targeted In recovery technologies that will enable a realistic closure of the In cycle remains a key need for the EU.

For above mentioned reasons, there is an urgent need to increase public awareness and build public trust across the EU regarding the proper handling of e-waste and the importance of recycling devices that remain forgotten in drawers. Table 1 outlines the most important challenges and identifies selected target groups within the FPD circular economy.

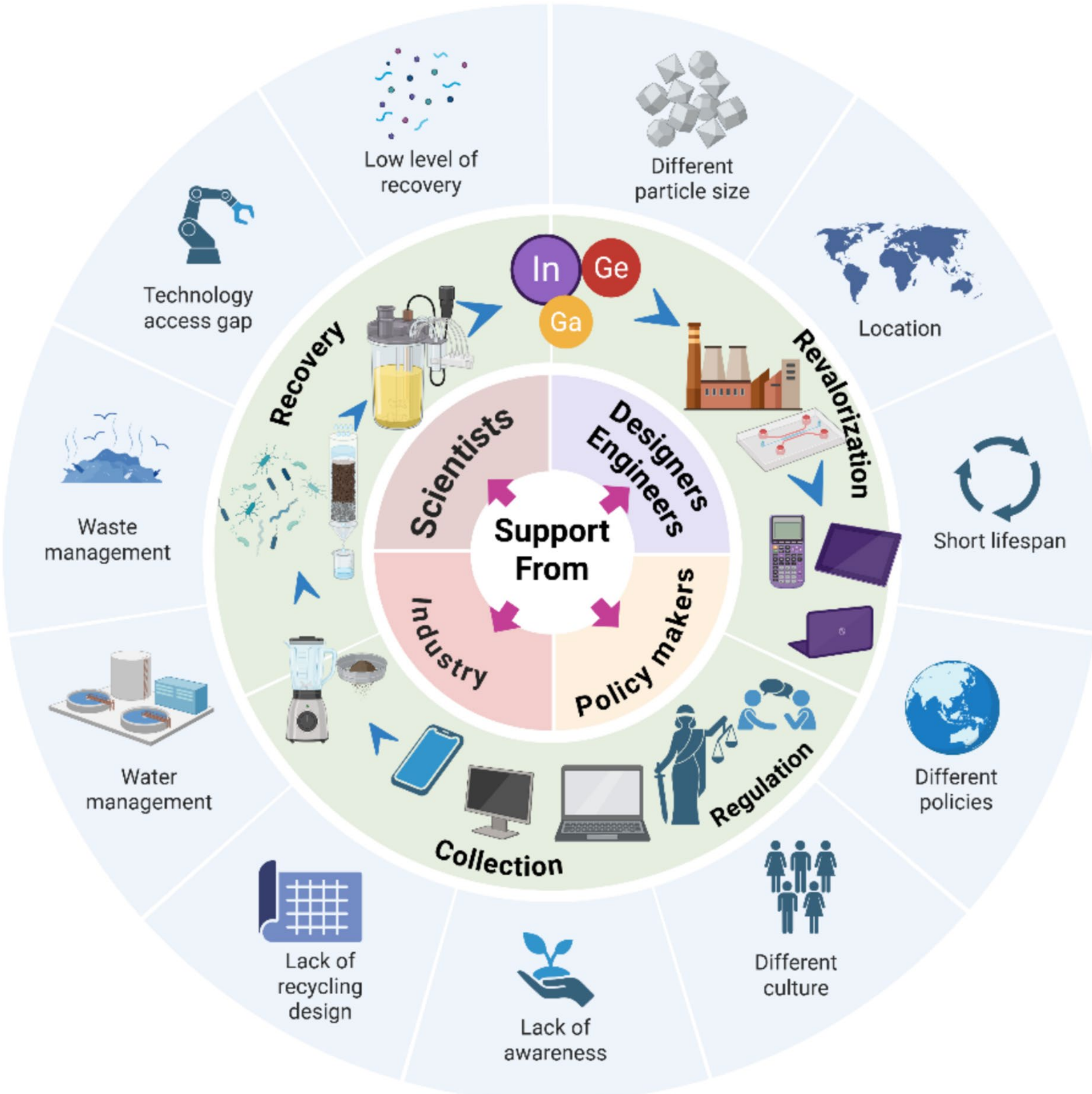

Fig. 1 Key stakeholders and issues related to FPD management

2 Flat panel displays characterization

2.1 Composition of FPD

FPD represent a diverse group of screen technologies, ranging from classic LCD and LED (Light Emitting Diodes) to more modern OLED and QLED (Quantum Dot LED). LED is an improved version of LCD, but both technologies use similar structural layers (polarizers, electrodes, RGB filters), differing primarily in their backlighting systems and operating efficiency. A classification of FPD based on dominant technology and material characteristics is presented in Tables 2 and 3.

LCD consist of two parallel glass plates with transparent electrodes positioned between them, a liquid crystal layer sandwiched between the electrodes, and a colour filter attached to the outer

Table 1 Challenges in FPD recycling considering the main target groups

Target group	Challenges
Manufacturers	Use of non-toxic, sustainable, and recyclable materials Minimization of hazardous substances (e.g., Pb, Hg, Ca, As) Effective design strategies for modularity and ease of disassembly to facilitate repairs, upgrades, and FPD recycling Applying advanced technologies to incorporate recycled or organic materials into new displays without compromising performance Partnerships with recycling companies for EoL product recovery
Consumers	Access to clear information on the environmental impact and recyclability of FPD products Incentive programs (e.g., buy-back or trade-in options) to encourage responsible disposal of old devices Clear, simple and available recycling opportunities
Recycling industry	Implementing advanced technologies to recover rare and valuable materials from FPD (e.g. In, REE (Rare Earth Elements)) Development of systems to efficiently separate and process toxic components (e.g., Pb, Hg) from FPD Collaboration with manufacturers to close material loops by supplying secondary raw materials
Researchers	Work on effective and environmentally friendly recycling techniques in metal separation from glass Optimizing metal concentration techniques in the leachate, ensuring cost-effective recovery Separation of metals from the leachate Collaboration opportunities with industry stakeholders to pilot innovative solutions, e.g., in the field of biotechnology Platforms to share findings with industry, policymakers, and the public
Educators	Raising awareness about the need to recycle FPD and WEEE (Waste from Electrical and Electronic Equipment), as well as promoting lesser-known and under-publicized green solutions within society Curricula that incorporate sustainability and circular economy principles into engineering and design education High quality education with the interdisciplinary approach necessary for complex solution in line with circular economy principles

surface of the electrodes (Fig. 2). Additionally, the structure includes display glass, a reflective mirror, and a polarizing layer tightly adhered to the glass. Polarizers typically consist of a layer of iodine-doped polyvinyl-alcohol (PVA, C_2H_4O) sandwiched between two protective sheets of tri-acetyl-cellulose (TAC, $C_{40}H_{54}O_{27}$) (Dodson et al. 2012; Song 2022). LCD monitors use cold cathode fluorescent lamps (CCFLs) for backlighting, whereas LED displays use light-emitting diodes. CCFLs use a gas discharge in a mercury-filled tube to generate ultraviolet radiation, which is converted into visible light by a phosphor coating [https://www.cevians.com/lcd-backlighting-history-applications-and-types/?utm_source=chatgpt.com], while LEDs generate light at the p–n junction of semiconductor materials (e.g., GaN/InGaN). LED backlights are thinner than CCFLs, offering better performance and enabling thinner panel designs (Anandan 2008).

OLED represent one of the most advanced and promising technologies for eco-friendly lighting solutions and vibrant colour display panels (Mandal et al. 2024). The structure of an OLED typically includes several layers: an anode, a Hole Injection Layer (HIL), a Hole Transport Layer (HTL), a Light-Emitting Layer (LEL), an Electron Transport Layer (ETL), an Electron Injection Layer (EIL), and a cathode. Light is emitted when electrons and holes are injected into the LEL from the electrodes and recombine. The colour of the emitted light depends on the specific emitter molecules used. QLED technology utilizes quantum dots, nanoparticles that emit light in specific colours depending on their size. When combined with LED backlighting, this technology delivers vivid colours, high brightness, and a wide tonal range in images (Bavarva and Bavarva 2018).

FPD are a key carrier of In, which is mainly used in the form of ITO as a transparent conductor in screens. Due to the growing production of electronic devices, FPD have become one of the largest consumers of this valuable metal. As shown in Fig. 3, FPD manufacturing is the largest In application group, encompassing touch screens, smart windows, and displays (e.g., laptops, monitors, and TV screens).

Table 2 The metal composition of FPD demonstrates significant inter-manufacturer variability, even for devices of the same type (Zhang et al. 2017; De la Torre et al. 2018; Willner et al. 2021; Qin et al. 2021; Trading econimics 2025; LME 2025)

Metals (mg/kg)	LCD monitors/screens	TV LED screen	Metal price ($/kg)	Average value of LCD ($/t)
In	300−1400	NA	354	106–495
Te	0.17	0.005	83	0.01
Ge	0.06	0.06	2000	0.12
Tl	0.09	0.81	4100	0.37
Cd	0.26	1.96	4.35	0.01
Co	2.46	1.56	33	0.081
Mn	15.62	9.54	2.3	0.036
Cr	100−2875	129.5	10	1–28
Cu	109.9−200	104.55	10	1–2
Ni	77.07	78.27	15	1
Pb	8.11	25.46	2	0.016
Sr	570.6−370,000	145.5	6	3.4
Sn	93−900	NA	35	3–31
Zn	26.3−6700	25.96	3	0.08–20
Fe	200−3600	NA	0.13	0.02–0.4
Si	254,000−689,700	NA	3	–

NA, Not available; Si comes from SiO_2

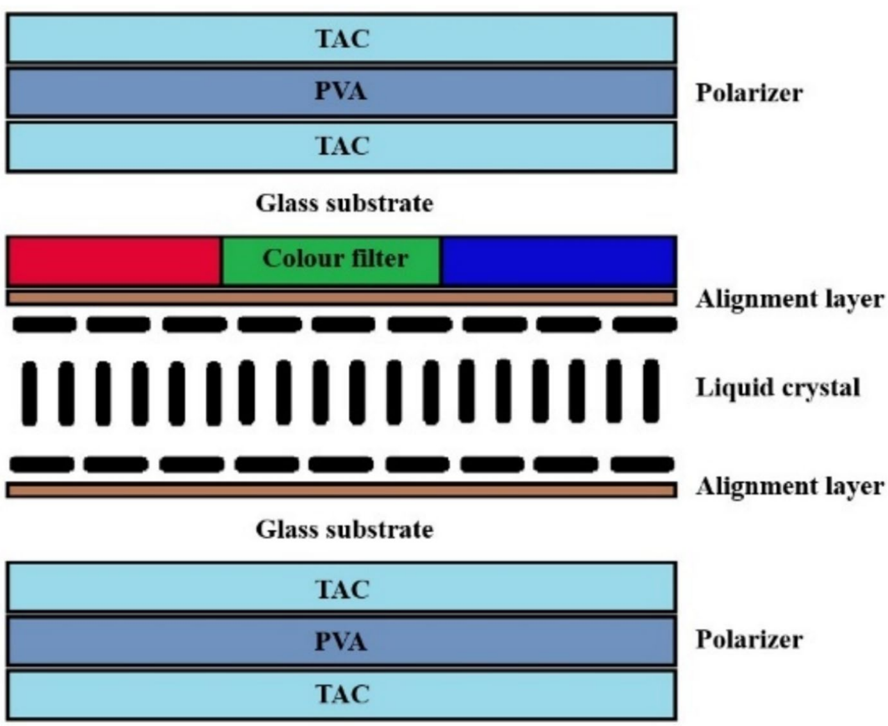

Fig. 2 Schematic composition of LCD

2.2 ITO characteristics

ITO is one of the most widely used transparent electroconductive materials in various electronic technologies due to its superior properties, such as relatively low electrical resistivity, environmental stability, high transparency to visible light, electric conduction, thermal reflectivity, excellent adhesion

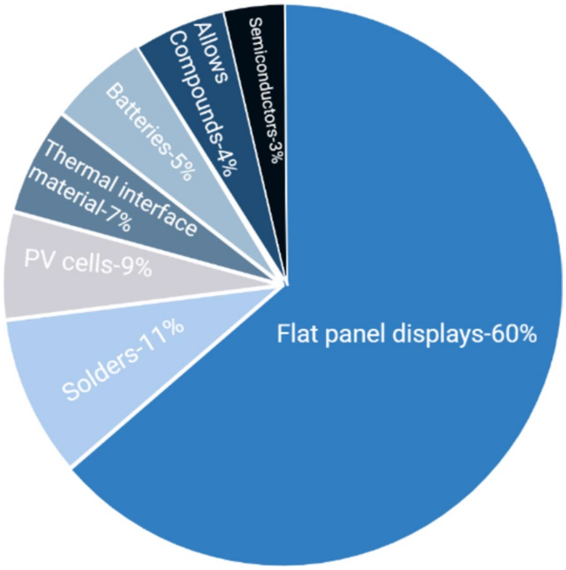

Fig. 3 The use of In in different applications (CRM list 2020)

to substrates, stable chemical properties, and ease of patterning (Alam and Cameron 2001; Kim et al. 2010, p. 20; Li et al. 2011; Amato et al. 2017). ITO is a mixture of In(III) oxide (In_2O_3) and tin(IV) oxide (SnO_2), typically composed of 80–90% In_2O_3 and 10–20% SnO_2 by weight (Yoo et al. 2022). The preparation of an ITO layer involves its evaporation onto glass, followed by etching to form the desired pattern. A polymer layer, sealing resin, and spacers are then applied, and the glass sandwich is filled with liquid crystal material. The transparent electrode pattern is created on the substrates by coating both the front and rear glass surfaces with a very thin layer of ITO. Depending on the FPD type, manufacturer, and the thickness of the ITO layer, the In content in FPDs varies greatly, ranging from 56 to 5600 mg/m^2 (Lee et al. 2013). The glass plates are typically coated with an ITO layer between 0.1 and 0.3 µm thick (Kim 2005). For example, in industrially shredded LCD glass, the In concentration was found to be 200 mg/kg glass (Yang et al. 2013), 330 mg/kg glass in LCD TVs (Yen et al. 2016), or 530 mg/kg glass in PC monitors (Savvilotidou et al. 2015). The average content of In is assumed in the range 100–300 mg In/kg (Wang 2009; Zhang et al. 2015), but values can reach up to 1400 mg In/kg when the polymer film attached to the screen is removed before processing (Silveira et al. 2015).

In addition to In, various types of FPD contain a range of other valuable or potentially hazardous metals. Backlight units (BLUs) in LCDs, especially those using cold cathode fluorescent lamps (CCFL), contain rare earth elements such as Y and Eu, as well as Hg. LED displays, particularly those used in BLUs, often include Ga, In, and Al in the form of GaN and InGaN semiconductors (Table 3). OLED panels are composed of approximately 85% organic material and glass (OLEDWorks 2025). Although considered more environmentally friendly due to the absence of mercury, OLED still contain metallic components such as Al (used in cathode layers), and rare metals like Ir or Pt in phosphorescent emitters (Yoon and Teets 2021; Kang et al. 2021). QLED displays incorporate quantum dots typically based on cadmium selenide (CdSe) or, in Cd-free alternatives, InP. Therefore, QLED displays may contain Ca, Se, In, P, and Zn, depending on the specific quantum dot formulation (Yu et al. 2022; Wang et al. 2023). Metal concentrations in FPD vary significantly depending on the device type, technology, and manufacturer. Details regarding the composition of FPD are provided in Tables 2 and 3. Although some of the elements listed in Table 2 have high unit prices, e.g., Ge at \$2000/kg or Te at \$83/kg, their trace concentrations in LCD mean that the raw material value per ton for these metals is usually very low (in the order of dollars or cents per ton). The real value in the FPD stream comes from metals with higher concentrations, e.g., Cu, but primarily In, which determines the profitability of LCD recycling. Based on the average In content in an LCD panel of 100–300 mg In/kg (Silveira et al. 2015) and a price of \$354/kg (Trading economics 2025) this translates to a value in the range of \$35–106/t of waste, which is significantly higher than the sum of the other elements (~\$10–85/t) listed in Table 2. This makes In a key metal in FPD recycling.

2.3 Characteristics of organic compounds in FPD

A typical FPD contains a wide array of organic compounds (Table 4), which, depending on their origin, include both synthetic and natural compounds. When classified by their chemical characteristics, these compounds fall into various chemical classes, including acrylate polymers, biphenyl derivatives, cellulose

Table 3 Characteristics of FPD materials (Bavarva and Bavarva 2018; Das et al. 2018; Das and Nandi 2021; Kumar et al. 2021; Jeon et al. 2022; Mandal et al. 2024)

Display	Display technology	Introduction to the market	Main components	Materials composition
LCD	Liquid crystals illuminated by LED or fluorescent lamps	1972	Glass substrates, plastic or foil	SiO_2, Al_2O_3, Fe_2O_3, B_2O_3, CaO, MgO, Na_2O, K_2O, PVA, TAC
			Anode	ITO, ZnO, indium-zinc-oxide (IZO), Au, Pt, Si
			Cathode	Mg/Ag, Al, Ba, Ca, In, ITO, IZO
			Coloured pigments (colour filters—CT glass) RGB	Pigments based on phthalocyanine R (red)—Diketopyrrolopyrrole (DPP) (Red 254), $C_{18}H_{10}Cl_2N_2O_2$ G (green)—with Cu or Zn in central metal, e.g., Pigment Green 36 (PG36), phthalocyanine $32Br_6Cl_{10}CuN_8$, B (blue)—e.g., copper phthalocyanine (CuPc), $C_{32}H_{16}CuN_8$
			Thin film transistors (TFT)	Metal-oxide (e.g. Zn, Cu, Ni), IGZO indium-gallium-zinc-oxide
			In LCD—backlights are cold cathode fluorescent lamps (CCFL) or LED	CCFL: mixture of inert gases Ne and Ar, trace amounts of Hg vapor, phosphors: Ce with Y, Al (YAG: Ce^{3+}) and $CaAlSiN_3$: Eu^{2+} (CASN: Eu^{2+})
LED	LCD displays with LED backlight	1997		LED: Semiconductor chips GaAs, GaN, InGaAs, InGaN, phosphor, Ce^{3+}/Eu^{2+} (CaAlSiN3:Eu^{2+}/Ce: $Y_3Al_5O_{12}$/$Tb_3Al_5O_{12}$:Ce), Pb
OLED	Organic diodes that emit light without the need for additional backlighting	2003	Hole Injection Layer (HIL)	Hexa-azatriphenylene Hexa-carbonitrile (HATCN)
			Hole Transport Layer (HTL)	Poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT: PSS), N, N-diphenyl-N, N-bis(3-methylphenyl)-1,10-biphenyl-4,4-amine (TPD), and N, N-Bis(naphthalen-1-yl)-N, N-bis(phenyl)benzidine (NPB) etc
			Light-Emitting Layer (LEL)	Polyfluorene (PFO), GGH1, Alq
			Electron Transport Layer (ETL)	Polyethyleneimine ethoxylated (PEIE), 2-(4-Biphenyl)-5-(4-tert-butylphenyl)-1,3,4-oxadiazole (PBD), tris(8- quinolinolato) aluminium (Alq3) etc
			In OLED: electron injection layer (EIL)	LiF, Liq, Py-hpp2, LiF, NaF, or CsF, Li, Ca, or Ba
QLED	Quantum dots—tiny nanocrystals that emit light when they get excited	2017	Quantum dots	Cadmium selenide (CdSe), cadmium sulphide (CdS), lead selenide (PbSe), lead sulphide (PbS), indium arsenide (InAs) and indium phosphide (InP)

Table 4 Chemical diversity of synthetic and natural organic compounds in devices with liquid crystal display (LCD) technology

Chemical class	Selected examples	Potential application areas	Source
Acrylate polymers	Acrylic resin, polyacrylamide, poly(butyl acrylate), poly(methyl methacrylate)	Front cover and back cover of monitors LCM alignment layer LCD screen Optical diffuser in direct-lit backlight unit UV sealant in the LCD panel assembly	Peng (2003); Kim (2005); Juchneski et al. (2013); Lee et al. (2022)
Biphenyl derivatives	Biphenyls/bicyclohexyls, cyanobiphenyls, fluorinated biphenyls, and analogues	LCM	Liang et al. (2021); Tao et al. (2022)
Cellulose derivatives	Carboxymethyl cellulose, triacetyl cellulose, ethyl cellulose, hydroxypropyl cellulose	LCM alignment layer Polarizer film	Mori et al. (1999); Yan et al. (2001); Suzuki et al. (2015); Wang et al. (2025)
Organobromides	Polybrominated diphenyl ethers	Flame retardants in plastics	Peeters et al. (2014)
Organophosphates	Bisphenol-A bis(diphenyl phosphate), resorcinol bis(diphenyl phosphate)	Flame retardants in plastics	Peeters et al. (2014)
Polyamides	Aromatic polyamides	LCM alignment layer	Akiyama et al. (2000)
Polyesters	Polybutylene terephtalate, polycarbonate, polyester resin, polyethylene terephthalate	Front cover and back cover of monitors LCD screen Optical diffuser in direct-lit backlight unit Plastic optical foils Support frames	Kim (2005); Juchneski et al. (2013); Ardente et al. (2014); Ferella et al. (2017)
Polyolefins	Polyethylene, polypropylene	Diffuser sheet Insulating strips	Ferella et al. (2017)
Proteins	Casein, gelatin, silk fibroin	LCM alignment layer Photopolymer material for dyed color filters	Sugiura (1993); Hou and Jeng (2020)
Vinyl polymers	Polystyrene, polyvinyl alcohol, polyvinyl chloride, polyvinylidene chloride	Back cover of monitors Internal cables LCM alignment layer Plastic optical foils Polarizer film	Costa et al. (2003); Ardente et al. (2014); Ferella et al. (2017); Kang et al. (2021); Tang et al. (2023)
Miscellaneous resins	Acrylonitrile butadiene styrene, cyclic olefin copolymer, epoxy resin, melamine resin, polyimide resin, polyurethane resin	Anisotropic conductive adhesive film Color photoresists material for color filter film Front cover and back cover of monitors LCM alignment layer UV sealant in the LCD panel assembly	Kim et al. (2003); Juchneski et al. (2013); Li et al. (2024)

derivatives, polyesters, proteins, vinyl polymers, and others.

Among the organic compounds in FPD, plastics and resins dominate due to their exceptional utility, which stems from a wide range of physicochemical properties (Peeters et al. 2014, 2015). The front and back covers, as well as the plastic housing that encases and protects the internal components of monitors, are made from various synthetic polymers. These include acrylate polymers (e.g., poly(methyl methacrylate)), polyesters (e.g., polycarbonate, polyethylene terephthalate), vinyl polymers (e.g., polystyrene), and several miscellaneous resins (e.g., acrylonitrile butadiene styrene) (Juchneski et al. 2013; Ardente et al. 2014; Peeters et al. 2015; Ferella et al. 2017).

The use of plastics in electronic devices is inextricably linked to the inclusion of various additives, particularly flame retardants (Liu et al. 2022; Mensah et al. 2022), which are crucial for reducing flammability and slowing the spread of fire. These additives predominantly fall within the category of organic compounds. Following the ban on widely used brominated flame retardants (Zhang et al. 2016; Altarawneh et al. 2019), such as polybrominated biphenyls and hexabromocyclododecane, that are now classified as persistent organic pollutants, modern FPD primarily incorporate organophosphates (e.g., bisphenol-A bis(diphenyl phosphate), resorcinol bis(diphenyl phosphate)) or alternative organobromides (e.g., certain polybrominated diphenyl ethers) (Peeters et al. 2015, 2014).

Liquid crystal (LC), from which LCD technology derives its name, consists of various organic molecules, commonly referred to as liquid crystal monomers (LCM), characterized by their nematic and thermotropic behaviours (Lee and Cooper 2008; Lee et al. 2011). To meet the key requirements of LCD, a mixture of different LCM is typically required, which is why several commercial mixtures are used, sometimes containing more than 20 distinct compounds (Tarumi et al. 1997; Kirsch and Bremer 2000). Although LCM are chemically diverse, they are generally aromatic-based polymers, typically derivatives of biphenyl. Three major groups are commonly identified: biphenyls/bicyclohexyls, cyanobiphenyls, fluorinated biphenyls, and their analogues (Liang et al. 2021; Tao et al. 2022).

The mixture of LCM is enclosed by an alignment layer on each side (Hoogboom et al. 2006), which ensures their macroscopic uniform alignment and is chemically even more diverse than external monitor subassemblies. Potential polymers used for the organic alignment layer include a range of synthetic polymers, such as acrylate polymers (e.g., polyacrylamide) (Lee et al. 2022), polyamides (e.g., aromatic polyamides) (Akiyama et al. 2000), and vinyl polymers (e.g., polystyrene, polyvinyl alcohol) (Costa et al. 2003; Kang et al. 2014), as well as synthetic cellulose derivatives (e.g., ethyl cellulose, hydroxypropyl cellulose) (Mori et al. 1999; Yan et al. 2001), and natural polymers, such as proteins (e.g., silk fibroin) (Hou and Jeng 2020).

In recent years, LCM have been increasingly recognized as emerging environmental pollutants released from waste FPDs. Comprehensive chemical screening of discarded LCD panels revealed the presence of 64 different LCM out of 93 targeted, including 19 biphenyl analogues, 6 cyanobiphenyls, and 39 fluorinated biphenyls (Liang et al. 2021). Concentrations in waste panels reached several milligrams per gram of material, with fluorinated and biphenyl-type monomers contributing over 90% of the total load. Based on these findings, the global direct release of LCM from LCD waste was estimated at 1.07–107 kg per year, with projections of significant growth as LCD disposal increases (Liang et al. 2021).

Environmental monitoring has further confirmed LCM contamination in air, dust, sediments, and even human serum, demonstrating their persistence, bioaccumulation potential, and toxicological relevance (Ge et al. 2023). Field studies in China and other regions have identified LCM in soil, river sediments, and atmospheric particles near e-waste recycling sites, suggesting their mobility and environmental transport (Tao et al. 2022; Yao et al. 2023; Xie et al. 2024). Laboratory and in vivo studies additionally highlight their potential to induce oxidative stress, endocrine disruption, and developmental toxicity in aquatic and terrestrial organisms (He et al. 2024b, a; Cheng et al. 2024). Finally, reviews of their chemical properties emphasize that halogenated and cyano-substituted LCM are particularly problematic due to their high stability and low biodegradability, qualifying them as candidates for persistent organic pollutants (Li et al. 2018; Su et al. 2022; Wang et al. 2024).

3 Overview of recycling technologies

LCD are now being outpaced by other display technologies but have not been entirely left behind. Among FPD, LCD still hold the highest market share and are widely used in notebooks, organizers, mobile phones, pocket calculators, measuring and control instruments, electronic games, TVs, audio–video equipment, PC monitors, and many other devices (Fontana et al. 2020). LCD can be broken down into several key components: metallic parts (Al and Fe), plastic casings, optical foils, the light guide (made of

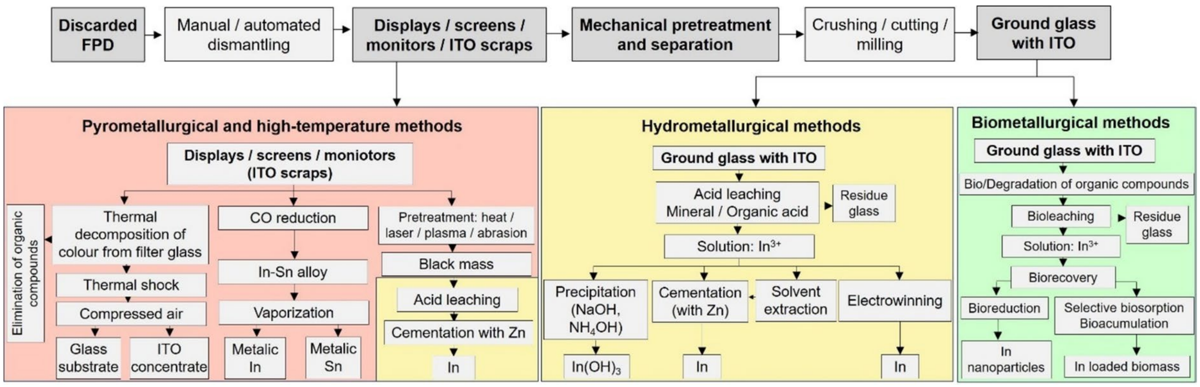

Fig. 4 Schematic representation of possible pathways for processing FPD and In recovery on a laboratory scale—three approaches within the recycling chain: pyrometallurgical, hydrometallurgical and biometallurgical

poly(methyl methacrylate), PMMA), printed circuit boards (PCBs), cables, the backlight (e.g., CCFLs), and the glass panel (the primary functional part) (Forte 2014). Recycling these materials involves a disassembly step aimed at removing hazardous components (e.g., CCFLs) and recovering valuable ones (such as PCBs, metallic fractions, and plastic casings) for further treatment (Buchert et al. 2012). As discussed in Sect. 2.2, In content in FPD end products varies widely due to technological differences between display types and generations, product structure, and application specifics (Horta Arduin et al. 2020; Xiao et al. 2026). This results in strong chemical heterogeneity of the material and dispersion of In in the waste. Therefore, pretreatment is crucial for concentrating In and increasing recovery. Although pretreatment increases initial operating costs, it can improve the profitability of In recovery by increasing the In concentration in the feedstock and reducing the volume subjected to leaching and extraction processes (Savvilotidou et al. 2019; Becci et al. 2024).

Mechanical recycling technologies are well-developed, but the recovery of In from FPD remains a challenge. This difficulty applies not only to In, but also to other critical metals, such as Ga, Ge, and rare earth metals, due to their low concentration, dispersion within electronic components, and the diversity of products, which exhibit varying concentrations and material heterogeneity. Furthermore, these products are neither designed nor assembled with recycling principles in mind (Willner et al. 2021). The main challenge lies in developing cost-effective recycling solutions for materials that are integrated into alloys, composites, or tightly packed within material structures, which complicates disassembly. In recent years, numerous studies on In recovery from FPD have been published; however, most have been conducted only at the laboratory scale, and a fully developed recycling technology is still lacking (Fontana et al. 2020). Figure 4 presents possible ways of FPD waste processing and In recovery, including three approaches in the recycling chain: pyrometallurgical and hydrometallurgical processes, and, as a promising alternative, the biometallurgical approach.

Indium recovery from LCD panels has been investigated using various methods, including dissolution, extraction, separation, and purification (Zhang et al. 2015; Amato and Beolchini 2018), leaching processes (Rocchetti et al. 2015; Fontana et al. 2020; Qin et al. 2021), and solvent extraction (Ruan et al. 2012; Pereira et al. 2018). Literature data indicate that hydrometallurgical treatment is the most frequently used method for recovering In from waste panels (Zhang et al. 2015; Fontana et al. 2020).

The primary focus of research into recycling technologies for FPD waste has been on the recovery of inorganic components, particularly rare earth metals (e.g., Ce, Eu, Ga, Ge, In) (Ruiz-Mercado et al. 2017; Zheng et al. 2023) and other inorganics identified by the European Commission as CRMs (Horta Arduin et al. 2020). However, it is essential to recognize that a variety of organic compounds are crucial for the functionality of electronic devices, and their recycling should not be neglected.

The development of recycling technologies generally involves the following steps:

- Pretreatment aimed at improving the collection of the ITO layer from FPD before metal dissolution processes;
- metal dissolution, targeting the extraction of all desired metals from FPD waste;
- metal recovery, using various methods to separate metals from the mixtures obtained after leaching/bioleaching, and production of specific valuable products.

3.1 Pretreatment

3.1.1 Conventional methods

Several pretreatment methods have been tested to improve the collection of the ITO layer from FPD glass prior to metal dissolution processes. These methods can be classified into mechanical, thermal, and magnetic approaches, each with distinct advantages and limitations.

3.1.1.1 Mechanical Pretreatment Stępień et al. (2017) highlighted the importance of the initial processing of LCD screens, which includes dismantling and crushing prior to acidic leaching. This step helps minimize metal encapsulation in organic layers, thereby enhancing the recovery of metals such as In. Traditional mechanical separation technique include brushing, mechanical exfoliation with a negative-pressure dry polisher (Wang et al. 2017), and mechanical stripping (Zhang et al. 2017). Lahtela et al. (2019) found that brushing with sanding abrasion effectively removed ITO layers from LCD glass and enabled the recovery of 96.2% In. Size reduction is another common pretreatment step conducted prior to leaching. Three different milling technologies (cutting, blade, and rod milling) were tested, and In was found to be concentrated in the finest fraction (< 212 μm), with the best results obtained after rod milling (around 51 wt% of < 212 μm fraction after 30 min of milling in wet conditions, yielding 276.6 ppm of In) (Ferella et al. 2017). However, increasing milling time can reduce In leaching efficiency, as the average particle size of waste LCD panels initially decreases but later increases due to the agglomeration of smaller particles among each other (Lee et al. 2013). For example, non-crushing methods have been tested in three different ways: i) leaching of upper LCD glass after cutting it into 4 × 4 cm pieces (Zhang et al. 2017), ii) electrical disintegration to separate the two glass substrates, thereby enabling higher leaching capacity for In from ITO compared to conventional grinding (Dodbiba et al. 2012), iii) direct leaching of 5 × 5 cm LCD scraps (Fontana et al. 2015). The rate of In dissolution from unground samples was found to be higher due to differences in vibration frequencies between the vitrified surfaces of LCD waste and the ITO thin-film, which cause detachment of the In-rich ITO layer (Fontana et al. 2020).

3.1.1.2 Thermal Pretreatment Thermal processes are used as a pretreatment to remove organic components (plastics, binders) from shredded LCD, preparing the material for subsequent hydrometallurgical processes (Fig. 4). Pyrolysis, a thermal decomposition process, is widely used for FPD recycling and typically conducted at elevated temperatures (around 450 °C) in the absence of oxygen (Wang and Xu 2016; Fontana et al. 2020; Eluri et al. 2025). However, key challenges arise during this process. Polyimide alignment layers can experience significant thermal degradation, leading to the formation of potentially toxic byproducts through interactions with liquid crystal monomers (Zhu et al. 2021). Certain liquid crystal monomers, particularly fluorinated biphenyls, represent persistent organic pollutants that can be released during pyrolysis, posing environmental and health risks (Liang et al. 2021; Yang et al. 2024). Lahtela et al. (2019) tested heat and plasma treatment prior to mechanical brushing but found that these thermal pretreatments did not improve the yield or purity compared to direct brushing alone. However, laser treatment caused the ITO layer to evaporate rather than mechanically remove it, making it a potentially promising option for metal recovery through gas capture systems. To address the challenges associated with pyrolysis, innovative pretreatment strategies such as alkaline or acidic hydrolysis can precede thermal treatment to improve separation (Cuvilas and Yang 2012), while co-pyrolysis with biomass materials has shown promise in enhancing efficiency and reducing harmful emissions (Shen et al. 2018).

Pyrometallurgy is generally less suitable for direct FPD recycling compared to hydrometallurgy or combined pyro-hydrometallurgical methods. FPD contain specific components like In and rare earth elements (e.g., Eu, Gd), which are highly dispersed in electronics, and pyrometallurgy is most suitable for sources with relatively high concentrations of target metals (Sun et al. 2017; Battelle 2023). Therefore, most studies on In recovery from FPD, are still only at a laboratory scale (Fontana et al. 2020) and are focused on more precise and selective hydrometallurgical methods with higher recovery purity.

3.1.1.3 Magnetic Pretreatment Magnetic separation has emerged as a valuable pretreatment method for In recovery from LCD waste. Recent findings by Willner et al. (2025) demonstrate that despite In being non-magnetic, it accumulates predominantly in ferromagnetic fractions, suggesting its association with Fe-bearing phases in the LCD matrix. In coarse fractions (> 1 mm), In was exclusively detected in the magnetic fraction at 244 mg/kg with extremely elevated Fe content (450,055 mg/kg), while remaining undetectable in non-magnetic counterparts. Similarly, in fine fractions (< 1 mm), In was present only in the magnetic portion (71 mg/kg). This indicates that In is likely entrapped within ferromagnetic phases in the original material, rather than being co-precipitated during leaching as previously suggested by Toache-Pérez et al. (2020, 2022). These findings highlight magnetic separation as a promising pre-concentration step that can enhance downstream hydrometallurgical processing efficiency.

3.1.2 A perspective technology: application of bacterial processes

Although significant progress has been made toward developing more environmentally friendly pretreatment methods within traditional processes, microbial biotechnological processes may offer a more sustainable alternative with a reduced carbon footprint and transformation capacity of new persistent organic pollutants, such as fluorinated biphenyls into more biologically accessible intermediates (Zhu et al. 2024; Li et al. 2025). While no studies have yet investigated the use of bacterial processes for removing organic material from FPDs, we conducted a comprehensive literature review and summarize here several promising bacterial strategies for this purpose.

The remarkable metabolic diversity of microorganisms, particularly chemoorganoheterotrophs, position them as strong contenders to replace pyrolysis in recycling the organic compounds found in FPD. Interestingly, despite the wide array of organic compounds present in a typical FPD, as listed in Table 4, nearly all are biodegradable, including synthetic organic compounds (Table 5). This biodegradability likely stems from the structural resemblance between synthetic organics and naturally occurring molecules, enabling microorganisms to utilize existing enzymes for their degradation (Ru et al. 2020; Ali et al. 2021).

While the innate biodegradation potential of microorganisms is undeniably valuable, the recycling of organic substances can still be optimized. One approach involves employing microbial consortia, which act synergistically as different taxa perform distinct steps of biotransformation, enabling the breakdown of complex molecules that a single species could not manage alone. Another promising avenue lies in the bioengineering of biodegradation-capable strains, focusing particularly on enhancing their enzymes. Moreover, genetic engineering could extend the ability to degrade synthetic organic compounds to other microorganisms, further broadening their application (Pant 2014; Han et al. 2022; Golzar-Ahmadi et al. 2024).

A promising perspective strategy for the degradation and subsequent utilization of organic compounds in FPD waste recycling may involve the application of acetic acid bacteria (AAB). AAB, Gram-negative and obligate aerobes of the family *Acetobacteraceae*, are among the most renowned industrial bacteria, with the genera *Acetobacter*, *Gluconacetobacter*, *Gluconobacter*, and *Komagataeibacter* being particularly prominent (Raspor and Goranovic 2008; Saichana et al. 2015). While their name reflects only their ability to convert glucose and ethanol into acetic acid, AAB oxidize various sugars and alcohols incompletely, yielding a spectrum of organic acids such as arabonic, butyric, galactonic, gluconic, lactic, pyruvic, and succinic acids (Mamlouk and Gullo 2013; Zhang et al. 2023). Furthermore, they hold economic importance due to their lesser-known ability to produce extracellular polysaccharides, most notably bacterial cellulose (BC), which forms a gelatinous membrane, the pellicle, on the surface of liquid culture (Gullo et al. 2018), as well as acetan and acetan-like polysaccharides (Trček et al. 2021).

The potential use of organic compounds from e-waste, often considered to have little remaining economic value, can be well illustrated at least as a partial substitute of expensive synthetic organic material by organic compounds recovered from LCD

Table 5 Biodegradability potential of synthetic and natural organic compounds in devices with LCD technology

Chemical class	Microorganisms	Biodegradation outline	Key reviews
Acrylate polymers	*Alicycliphilus*, *Arthrobacter*, *Aspergillus*, *Bacillus*, *Penicillium*, *Pseudomonas*, *Rhodococcus*, *Streptococcus*	Initially, enzymatic attacks (e.g., amidases, esterases, lipases, and nitrile-degrading enzymes) on amide, alkyl, and nitrile side groups lead to the formation of polyacrylic acid This is followed by aerobic or anaerobic cleavage of carbon backbone via multiple pathways (e.g., β-oxidation-like-head-to-head or tail-to-tail pathways, three-steps pathway, α-oxidation-like mechanism, fermentative pathway)	Bettencourt et al. (2010); Joshi and Abed (2017); Nyyssölä and Ahlgren (2019); Gaytán et al. (2021)
Biphenyl derivatives	*Achromobacter*, *Acinetobacter*, *Alcaligenes*, *Bacillus*, *Burkholderia*, *Comamonas*, *Corynebacterium*, *Pseudomonas*, *Ralstonia*, *Rhodococcus*, *Sphingomonas*	Biodegradation is best studied on polychlorinated biphenyls – harmful persistent organic pollutants The aerobic biphenyl degradation pathway involves various biphenyl metabolic enzymes (e.g., biphenyl-2,3-dioxygenase, dihydrodiol dehydrogenase, 2,3-dihydroxybiphenyl dioxygenase, HOPDA hydrolase) encoded by the *bph* gene cluster Halogenated biphenyls are subjected to anaerobic reductive dehalogenation	Borja et al. (2005); Pieper and Seeger (2008); Furukawa and Fujihara (2008); Field and Sierra-Alvarez (2008),
Cellulose derivatives	*Alcaligenes*, *Aspergillus*, *Bacillus*, *Bacteriodes*, *Clostridium*, *Erwinia*, *Neisseria*, *Pseudomonas*	Biodegradation is driven by cellulases, including endoglucanases that break internal bonds, and cellobiohydrolases, which target the terminal ends Acetylated cellulose is degraded through the synergistic action of lytic polysaccharide monooxygenases (random oxidative cleavage), cellulases (glycosidic bonds cleavage), and acetyl esterases (deacetylation)	Polman et al. (2021); Pooja et al. (2023)
Organobromides	*Burkholderia*, *Dehalobacter*, *Dehalococcoides*, *Desulfitobacterium*, *Pseudomonas*, *Pseudonocardia*, *Rhodococcus*, *Sphingomonas*, *Sulfurospirillum*	Anaerobic debromination is a potential biotransformation pathway for polybrominated diphenyl ethers, where higher congeners are gradually reduced to compounds with fewer bromine atoms, potentially resulting in completely dehalogenated diphenyl ether Under aerobic conditions, diphenyl ethers or bromodiphenyl ethers may be transformed into bromophenol or bromophenolic congeners, with the process possibly including hydroxylation	Chen et al. (2015); Waaijers and Parsons (2016); Lumio et al. (2021)

Table 5 (continued)

Chemical class	Microorganisms	Biodegradation outline	Key reviews
Organophosphates	*Arthrobacter*, *Aspergillus*, *Bacillus*, *Enterobacter*, *Flavobacterium*, *Penicillium*, *Pseudomonas*, *Sphingomonas*	Generally, the biodegradation of organophosphorus compounds begins with the hydrolytic cleavage of phosphate ester groups by organophosphate hydrolase The enzyme, also referred to as phosphotriesterase for its ability to hydrolyze triester bonds, is encoded by the *opd* (organophosphate-degrading) gene	Singh and Walker (2006); Waaijers and Parsons (2016)
Polyamides	*Agromyces*, *Arthrobacter*, *Flavobacterium*, *Phanaerochaete*, *Pseudomonas*, *Trametes*	Similar to natural proteins, synthetic polyamides are polymers in which repeating units are linked by amide bonds, making them susceptible to hydrolytic cleavage by enzymes such as proteases and amidases Synthetic polyamides are typically less sensitive to biodegradation, likely due to their high crystallinity, as hydrogen bonds between polymer chains might hinder the action of microbial enzymes	Krueger et al. (2015); Zheng et al. (2024)
Polyesters	*Alcaligenes*, *Bacillus*, *Cryptococcus*, *Leptothrix*, *Paenibacillus*, *Pseudomonas*, *Streptomyces*, *Thermobifida*	Polyesters undergo biodegradation through the enzymatic cleavage of their hydrolyzable ester bonds, a process driven by esterolytic enzymes such as esterases, lipases, and proteases The degradability potential depends on the backbone structure: aliphatic polyesters degrade more easily due to their flexible polymer chains, whereas aromatic polyesters are more resistant to microbial depolymerases	Shah et al. (2014); Urbanek et al. (2020)
Polyolefins	*Acinetobacter*, *Aspergillus*, *Bacillus*, *Engyodontium*, *Phanerochaete*, *Pseudomonas*, *Rhodococcus*	The polyolefin backbone primarily consists of C–C and C-H bonds, which are oxidized by oxidative enzymes (e.g., alkane hydroxylase, laccase, manganese peroxidase) Long polymer chains are then hydrolyzed into smaller hydrocarbons with up 50 carbon atoms that can be readily assimilated	Ammala et al. (2011); Restrepo-Flórez et al. (2014); Kumar Sen and Raut (2015); Zhang et al. (2022)

Table 5 (continued)

Chemical class	Microorganisms	Biodegradation outline	Key reviews
Vinyl polymers	*Alcaligenes*, *Bacillus*, *Geotrichum*, *Penicillium*, *Pseudomonas*, *Sphingomonas*, *Sphingopyxis*, *Streptomyces*	The biodegradation of polyvinyl alcohol begins with oxidation, where polyvinyl oxidase (secondary alcohol oxidase) targets one or two neighboring hydroxyl groups, converting them into monoketones or diketones The resulting carbonyl structures are then hydrolyzed: monoketones by aldolase-type enzyme and diketones by β-diketone hydrolase	Kawai and Hu (2009); Halima (2016)

waste and use it for revalorization to BC-material. While BC and plant cellulose are chemically identical, BC is distinguished by its absence of impurities, such as hemicellulose, lignin, and pectin, as well as its superior physicochemical properties, including a high degree of crystallinity and polymerization, pronounced hydrophilicity, enhanced tensile strength, excellent biocompatibility, and remarkable biodegradability (Gorgieva and Trček 2019; Naomi et al. 2020). However, the high production costs of BC, often significantly exceeding those of conventional plant cellulose, pose a major obstacle to its broader application (Islam et al. 2017).

A key factor driving these costs is the reliance on expensive synthetic growth media, which typically use glucose as a carbon source alongside various costly nutrient. While these media significantly enhance BC yields, their high-cost limits BC's range of applications. This issue has long been recognized, and the development of cost-effective yet efficient growth media is one of the most thoroughly reviewed topics in the field (Velásquez-Riaño and Bojacá 2017; Islam et al. 2017; Hussain et al. 2019; Ul-Islam et al. 2020; Swain et al. 2022; El-Gendi et al. 2022; Patel et al. 2023). Waste materials, such as agricultural, food and beverage, municipal, and textile wastes, are frequently proposed as alternatives to synthetic media, offering a dual benefit: reducing production costs and addressing the environmental challenge of waste disposal.

Among newer waste types, e-waste particularly in its shredded dust (or powder) form, emerges as a promising yet underexplored option for BC production. While microorganisms and their biotechnological processes are often viewed primarily as alternative recycling methods, they also provide an added benefit, the generation of valuable microbial products. For example, integrating shredded dust e-waste into existing growth media could lower costs while maintaining efficiency. BC-producing AAB are an excellent case in point, as they could potentially utilize organic compounds from e-waste as an alternative, low-cost carbon source for producing versatile and widely applicable BC (Fig. 5).

Due to the intrinsic presence of numerous enzymes that enable various microorganisms to biodegrade organic compounds in FPD, as highlighted in Table 5, AAB naturally demonstrate potential for growth on e-waste. The first group of organic compounds that

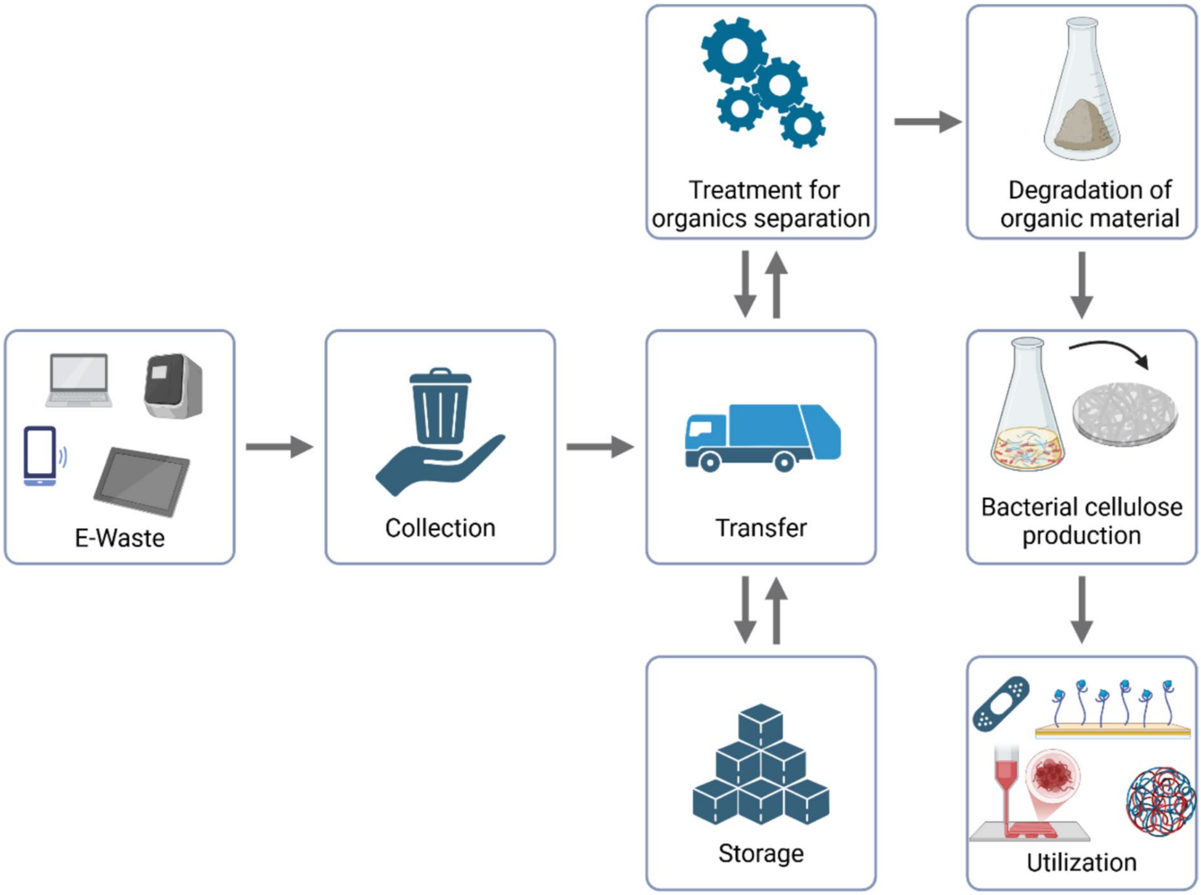

Fig. 5 Conceptual framework for valorising organic materials from electronic waste into bacterial cellulose for diverse applications. This organic material recovery and conversion represent the first step in a comprehensive e-waste recycling process, with metal recovery following in subsequent stages (not shown)

AAB could exploit as a carbon source includes various cellulose derivatives. As cellulose-producing organisms, much like plants, AAB not only carry the cellulose synthase operon but also a suite of additional genes essential for cellulose biosynthesis, including those encoding different cellulases (Tonouchi 2016). Among these, at least two cellulases have been identified in AAB: carboxymethyl cellulase (CMCase) (Husemann and Werner 1963) and β-glucosidase (Tonouchi et al. 1997). CMCase, an endo-1,4-β-glucanase, is thought to play a role in remodeling cellulose microfibrils, such as by reducing tensional stress (Tonouchi 2016). This cellulase is particularly efficient at hydrolyzing water-soluble forms of cellulose, including carboxymethyl cellulose, hydroxyethyl cellulose, and cellodextrin (Ito et al. 2004).

Through hydrolytic cleavage, AAB could metabolize not only cellulose derivatives but also other hydrolyzable organic compounds (or their breakdown products) present in FPD. Many biodegradable polymers owe their degradability to the abundance of various hydrolyzable bonds, which are targeted by diverse hydrolases such as esterases (e.g., lipases and phosphatases), glycosidases, and proteases (Shah et al. 2014). These enzymes are widely distributed across microorganisms, including AAB. In general, non-hydrolyzable polymers are considered less biodegradable than their hydrolyzable counterparts (Narancic and O'Connor 2019).

Since some organic compounds in FPD, such as biphenyl derivatives and organobromides, require dehalogenation, AAB with specific dehalogenases could effectively carry out this biodegradation step.

Zhurenko et al. (2003) reported a case of dehalogenation in *Gluconobacter oxydans* IBRB-2 T, where the bacterium used 2,4,5-trichlorophenoxyacetic acid as its sole carbon and energy source, initially producing phenoxyacetic acid, followed by methyl-2,6-dioxo-4-hexenoic acid. Additionally, ’ene’ reductase from *G. oxydans* can perform a different type of dehalogenation—debromination of organic compounds, such as bromoesters (Nakano et al. 2019).

In addition to the specific, enzyme-facilitated degradation of organic compounds from FPD, AAB may also indirectly affect these compounds, particularly plastics and resins, by secreting organic acids such as acetic and gluconic acid. It is well established that organic acids formed through the oxidation of carbohydrates are highly active in the biodegradation process. Moreover, these acids lower the pH of the liquid medium in which the bacteria are cultured, which could further accelerate the surface erosion of various organic polymers (Ali et al. 2021). A possible mechanism through which organic acids enhance the bioavailability of both synthetic and natural polymers is acid hydrolysis (Olivato et al. 2012; Hocker et al. 2014). The organic products produced by the action of these acids, combined with the low pH of the growth medium, are more readily absorbed and utilized by microorganisms as a carbon source, even by those lacking the specific enzymes for biodegradation, which would otherwise prevent them from utilizing these compounds (Ali et al. 2021).

AAB are an excellent example, as their application in recycling e-waste extends beyond organic compounds in FPD. They can also play a role in the initial steps of bioleaching valuable metals. The solubilization of various metals is driven by organic acids, primarily acetic and gluconic acid, that AAB secrete into their growth medium (Mishra et al. 2023; Golzar-Ahmadi et al. 2024). Recent studies provide numerous examples of bioleaching involving AAB, with most research focusing on the genera *Acetobacter* (Groudeva et al. 2007; Shin et al. 2015; Jadhav et al. 2017; Qu et al. 2019; Kiskira et al. 2021), *Gluconobacter* (Bellenberg et al. 2021; Abhilash et al. 2022; Aston et al. 2022; Schueler et al. 2024; van Wyk et al. 2024), and *Komagataeibacter* (Hopfe et al. 2017, 2018; Horta Arduin et al. 2020; Beeler et al. 2024).

AAB demonstrate effectiveness in both direct and indirect bioleaching approaches: in the direct method, microorganisms are inoculated into the leaching medium alongside e-waste, while in the indirect method, e-waste is added only after the bacteria have been growing in the medium for a specific period (Qu et al. 2019; Kiskira et al. 2021; Schueler et al. 2024). Additionally, AAB can be employed solely as producers of organic acids. In such cases, the growth medium is centrifuged, and the resulting supernatant (cell-free spent medium) is used to treat e-waste (Jadhav et al. 2017; Qu et al. 2019; van Wyk et al. 2024). A unique bioleaching strategy involving BC-producing AAB utilizes kombucha cultures, which combine acetogenic AAB with yeast and lactic acid bacteria (LAB). In this setup, metal solubilization is achieved through the production of acetic and gluconic acid by AAB and lactic acid by LAB (Hopfe et al. 2017; Beeler et al. 2024).

3.2 Metal dissolution

3.2.1 Hydrometallurgical methods

Hydrometallurgical techniques represent a fundamental approach for extracting metals such as In from various feedstocks using aqueous solutions. This section focuses on the application of acidic leaching systems for the dissolution of In, particularly from ITO, in which In_2O_3 is the primary In-bearing phase. Emphasis is placed on the influence of the type of leaching agent, acid concentration, temperature, reaction time, and other operational parameters on leaching efficiency. The discussion also addresses differences in leaching kinetics and complexation stability, as well as the role of oxidative additives in enhancing metal recovery.

The input material (feed), leaching conditions and In yield achieved under different treatments are summarized in Table 6. Chemical leaching is a fundamental step in initiating the recovery process and is performed by contacting the (pretreated) material with an appropriate leaching agent. For In leaching, acidic leaching solutions are commonly used (i.e. HCl, H_2SO_4, HNO_3, or mixtures thereof). It has been found that HCl and H_2SO_4 provide better yields than HNO_3 (Virolainen et al. 2011; Fontana et al. 2015; Yang et al. 2016). The leaching kinetics of In in 1 M HCl are much faster than in 1 M HNO_3. Moreover, the stability constants of In-chloride complexes are higher than those of In-nitrate complexes, resulting in higher leaching efficiency with HCl compared to

HNO_3 (Yang et al. 2016). The basic steps of In leaching in HCl can be summarized as follows:

$$In_2O_3 + 6HCl \rightarrow 2InCl_3 + 3H_2O \quad (1)$$

$$InCl_3 + 6H_2O \rightarrow \left[In\left(H_2O\right)_6\right]^{3+} + 3Cl^- \quad (2)$$

$$SnO_2 + 4HCl \rightarrow SnCl_4 + 2H_2O \quad (3)$$

$$SnCl_4 + 2Cl^- \rightarrow \left[SnCl_6\right]^{2-} \quad (4)$$

$$In_2O_3SnO_2 + 10HCl \rightarrow 2InCl_3 + SnCl_4 + 5H_2O \quad (5)$$

The extraction of In(III) follows the order $HNO_3 > H_2SO_4 > HCl$ at low aqueous acidities below 2 M (Sato and Sato 1992), however, this order is reversed at higher acidities (Virolainen et al. 2011). The leaching efficiency of In in other two inorganic acids compared with HCl can be ranked as $HCl > H_3PO_4 > HClO_4$ (Zhang et al. 2020). The leaching of ITO in HCl, as shown in Eqs. 1–5 (Swain et al. 2016), involves the conversion of In_2O_3 into $InCl_3$, which dissolves as the trivalent hexa-aquo-complex $[In(H_2O)_6]^{3+}$. Similarly, SnO_2 is leached as $SnCl_4$, which dissolves as the divalent hexa-chloro-complex $[SnCl_6]^{2-}$ (Fontana et al. 2020). The addition of catalysts such as MnO_2 or H_2O_2 has been shown to enhance dissolution via a redoxolysis process (Zeng et al. 2015; Swain et al. 2016; Argenta et al. 2017). Acid concentration, reaction temperature, solid-to-liquid ratio, particle size of the samples, reaction and agitation time, catalysts, more efficient transformations and dissolution of metal ions have been the main mechanisms regulating reaction conditions (Zheng et al. 2023).

In addition to inorganic acids, some organic acids have also been used for In leaching. These include malic acid (1 M with 5% H_2O_2), with a leaching yield of 70.9% (Argenta et al. 2017); citric acid, with a yield of 98.9% (López-Yáñez et al. 2019); oxalic acid with maximum In yield of 95.45% (Li et al. 2020); and EDTA and RTA, with a relatively low yield of $\geq 80\%$ (Hasegawa et al. 2013). Compared to mineral (inorganic) acids, organic acids are milder, less toxic, more selective, more biodegradable under aerobic/anaerobic conditions, and easier to control during metal extraction. Oxalic acid, in particular, has demonstrated high leaching efficiency from LCDs because it maintains the proton concentration at levels optimal for In release while limiting the dissolution of other non-target metals (Cui et al. 2019; Zheng et al. 2023).

Increasing temperature generally enhances In leaching. Yang et al. (2016) reported that in 1 M HNO_3, In leaching required 4 days to reach equilibrium at 20 ± 2 °C, whereas it reached equilibrium in approximately 8 h at 80 ± 2 °C. This indicates an endothermic ($\Delta H > 0$) reaction process, explained by differences in standard enthalpies. However, the main disadvantage of high temperatures is the increased solubility of other materials, such as SiO_2 (Eq. 6), and the formation of crud in subsequent solvent extraction processes (Ritcey 1980; Yang et al. 2016). The optimal temperature range for acid leaching of In from LCD displays is 60–90 °C (Li et al. 2009, 2020; Rocchetti et al. 2015). Moreover, the leaching efficiency of In and Sn at 75 °C and 100 °C was found to be almost the same (Swain et al. 2016). In the case of oxalic acid solvent, the optimal temperature was 90 °C, yielding a maximum In leaching efficiency of 95.45%. Temperatures above 90 °C were not recommended due to boiling and decomposition of the acid into CO_2 and H_2O. A decreasing trend in maximum leaching efficiency was observed at lower temperatures, respectively 94.41% at 80 °C and 83.29% at 70 °C (Li et al. 2020). A similar temperature (90 °C) was also the best for In leaching in 1 M solutions of both malic and citric acids (Argenta et al. 2017).

$$SiO_2(s) + 2HCl \rightarrow H_4SiO_4 \quad (6)$$

Kang et al. (2014) noted that low metal concentrations in leachate solutions can be addressed by synthesizing zeolites, which help concentrate metal ions. In addition to In, other metals, such as rare and precious metals, are also targets of recovery technologies. Toache-Pérez et al. (2022, 2020) proposed an efficient and eco-friendly method for recovering Gd, Pr, Zn, Er, and Sn from LCD screen waste. Using ultrasound-assisted leaching and magnetic separation, recovery rates reached 87% for Gd and 85% for Pr, with magnetic residues enriched in Fe, Gd, and Pr. Subsequent metal recovery from leachates yielded 85% Gd, 87% Pr, 91% Zn, although lower values were observed for Er (12%) and Sn (25%). The Toache-Pérez et al. (2022) study showed improved results,

Table 6 Summary of extraction processes and recovery outcomes

Material source	Extraction method	Process conditions	In recovery	Source
Unground waste LCD screens	Inorganic and organic acid leaching	1 M H_2SO_4, 1 M HNO_3, organic acids -citric, glycolic, L-ascorbic, maleic and DLtartaric);3–168 h	> 90%	Schuster and Ebin (2021)
LCD screens from computer monitors and laptop screens	Sulfuric acid leaching	0.4 N H2SO4; 50% (w/v); 30 min	99.5%	Houssaine Moutiy et al. (2020)
LCD powder	Citrate leaching with hydrazine as reducing agent	1 M citrate, 0.2 M N_2H_4, pH 5, Solid-to-liquid ratio 20 g/L, pH: 5, using NaOH; 16.6 h	98.9%	López-Yáñez et al. (2019)
Waste Liquid Crystal Display (LCD) panel	Sulfuric acid leaching after hydrothermal pretreatment	0.5 M H_2SO_4, 70–80 °C, Solid-to-liquid ratio 1:2 g/mL; 40 min	97.25%	Cao et al. (2020)
TV and computer LCD panel waste,	Sulfuric acid leaching with membrane filtration	1 M H_2SO_4, 80 °C, Solid-to-liquid ratio 200 g/L; 2 min	94.1–99.8%	Lahti et al. (2020)
Waste LCD displays(14% polarizing film, 86% glass substrate)	Hydrochloric acid leaching	6N HCl, room temperature, Solid-to-liquid ratio 3 mL/g, 6 h	90%	Fontana et al. (2015)
LCD screens	Sulfuric acid leaching	0.2 M H_2SO_4, 50% w/v, T = 70 °C, t = 30 min, back-extraction with 1 M and 5 M HCl	78%	Fortin-Lecomte et al. (2022)
Discarded FPD, major LCD	Sulfuric and hydrochloric acid leaching	1 M H_2SO_4, 20 °C, back-extraction with HCl	–	Yang et al. (2016)
Waste LCD panels	Organic acid leaching	0.5 M oxalic acid, 30–90 °C, Solid-to-liquid ratio 50 g/L; 15–90 min	99.5%	Cui et al. (2019)
Waste LCD panel	Hydrochloric acid leaching	0.5 M HCl at 80 °C or 2 M HCl at 55 °C	> 90%	Illés et al. (2022)
Spent LCD screens	Siderophore desferrioxamine E leaching	5 M DFOE, 25 °C, Solid-to-liquid ratio 1 g/L, pH 5.5; Over 90 days	32%	Zheng et al. (2024)
Waste LCD panels	Ultrasound-assisted acid leaching	0.75 M H_2SO_4, 300 W of ultrasound, pH 3, extraction 20% DEPHA, 2 M HCl	80%	Zhang et al. (2023)
Crushed LCD displays (16 cm^2)	Physical–chemical four step process	Mixture of 1:5 (v/v) ethyl acetate and ultrapure water at 180 °C with a solid/liquid (S/L) ratio 70 g/L, after soft acid microwave-assisted extraction (0.25 M HCl, S/L ratio 20 g/L, 3 cycles of 30 s at 850 W microwave); 60 min	84%	Martelo et al. (2025)
Non crushing LCD	Utrasound-assisted hydrochloric acid leaching	0.8 M HCl, 300 W ultrasonic waves at room temperature, 1 h	96.8%	Zhang et al. (2017)

Table 6 (continued)

Material source	Extraction method	Process conditions	In recovery	Source
TV, PC, mobile LCD	Acid leaching	Aqua regia (HCl/HNO3, 3:1), 0.5 M H2SO4,2 h; 6 M HCl, 60 °C, 4 h	99,3%	Gabriel et al. (2020)

with recovery rates of 93% Er, 99% Gd, 72% Sn, and 97% In. This method outperformed conventional processes and demonstrated effective co-extraction of elements like Sn under optimized conditions.

3.2.2 Biometallurgical methods

Biometallurgy, based on green and environmentally friendly bacterial activity, offers processes that operate at lower temperatures, consume less energy, and have a smaller carbon footprint compared to traditional metallurgical technologies. The primary process used for metal dissolution is bioleaching, which employs specific acidophilic microorganisms to extract metals from low-grade ores or waste materials. One of the main advantages of bioleaching is the reduction of toxic waste and energy consumption, as the process occurs at near-ambient temperatures and requires minimal energy input (Brierley 2008; Johnson 2018). Furthermore, bioleaching allows for the selective recovery of metals, reducing the risk of contamination and enabling more efficient use of secondary raw materials (Işıldar et al. 2017; Rendón-Castrillón et al. 2023). For e-waste such as FPD, bioleaching holds particular promise due to the ability of microorganisms to dissolve difficult-to-reach metals such as In under milder and more sustainable conditions than those used in traditional hydrometallurgical techniques (Yaashikaa et al. 2022).

Although relatively few studies have focused specifically on FPD bioleaching, some published results are already available. It has been demonstrated that bioleaching of spent FPD is feasible and can achieve high In recovery efficiencies from ITO (55–94%, depending on experimental conditions). This indicates that bacteria could play a leading role in the development of new green technologies for LCD recycling.

Existing bioleaching approaches for recovering metals from waste FPD can be categorized into three main groups:

a) Application of chemoautotrophic bacteria
b) Application of heterotrophic microorganisms
c) Hybrid bioleaching combining autotrophic and heterotrophic microorganisms

a) Application of chemoautotrophic bacteria.

To bioleach metals from FPD waste, pure cultures or consortia of *A. thiooxidans* and *A. ferrooxidans* were most often tested. In these studies, adaptation was found to be a crucial step, resulting in higher recovery efficiency. Adapted bacterial cultures were able to grow under higher pulp densities, tolerate higher concentration of toxic metal ions, and attach more effectively to solid particles, which supported higher bioleaching efficiency (Willner et al. 2021; Khezerloo et al. 2023). Bioleaching efficiency varied depending on the target metal, e.g., In was recovered with efficiencies ranging from 55 to 100%, Sn with efficiency approximately 90% and Ga with 75–83% efficiency. Very high efficiencies were found for Ni and Cu, ranging from 97 to 100% and 83–100%, respectively. Strontium was the most challenging metal, with the bioleaching efficiencies ranging from 5 to 15%. A low pH below 3 was maintained throughout all processes. A summary of existing results is shown in the Table 7.

The *A. ferrooxidans* bioleaching system showed better metal extraction results than *A. thiooxidans*, especially for Sn, indicating the specific role of iron and *A. ferrooxidans* in Sn recovery (Willner et al. 2021). On the other hand, bioleaching with *A. ferrooxidans* was also associated with the formation of a passivation layer (jarosite or sulphur) on the surface of the powder, resulting in reduced metal recovery (Pourhossein et al. 2021).

Non-contact bioleaching enhanced leaching yields up to 100% from EoL LEDs (Pourhossein et al. 2022). This study demonstrated that the presence or addition of extrapolymeric substances not only adsorbed metal ions but also increased diffusion barriers, thus diminishing the transfer of metal ions from LEDs into bioleaching solution over an extended period.

Table 7 Application of autotrophic bacteria for metal recovery from FPD by bioleaching

FPD type	Organism	Efficiency (%)	Duration (days)	Process	Source
LCD	*A. thiooxidans*	100 In, 10 Sr	15	Adapted bacteria, initial pH 2.6, pulp density 1.6%, initial sulphur concentration 7 g/l	Jowkar et al. (2018)
	A. ferrooxidans, A. thiooxidans	55.6 In, 90.2 Sn	In 35 Sn 14	Adapted bacteria, 9 K medium, 2.5% pulp density, 9 K medium + 2 g elemental sulphur	Willner et al. (2018)
	A. ferrooxidans, A. thiooxidans	94.7 In, 98.2 Sn	35	Adapted bacteria, 1% pulp density, 30 °C	Willner et al. (2021)
	A. thiooxidans	100 In	6	Bacterial consortium enriched from aerobic activated sludge, 15 g/l LCD	Xie et al. (2019)
	A. ferrooxidans, A. thiooxidans	100 In, 15 Sr, 60 Al	18	6% pulp density, one-step, initial pH 2	Khezerloo et al. (2023)
	Adapted acidophilic consortium	50 In	10	Adapted bacteria, Pulp density 32.5 g/l, one step, initial pH 1.8	Constantin et al. (2024)
LED	*A. thiooxidans*	100 Cu, 100 Ni, 75 Ga	10	Contact/noncontact, single step, multistep	Pourhossein et al. (2022)
	A. ferrooxidans	83 Cu, 97 Ni, 83 Ga	15	Adapted bacteria, indirect bioleaching (step wise—biogenic ferric iron added several times), biogenic ferric ion addition 4–5 mg/l, pulp density 20 g/l	Pourhossein and Mousavi (2019)
OLED	*A. ferrooxidans*	100 In, 5 Sr	15	Adapted bacteria, 9 K medium, ferrous sulphate 13 g/l, solid content 3 g/l, elemental sulphur 5.6 g, initial pH 1.1	Pourhossein et al. (2021)
MPTS*	*A. ferrooxidans*	100 In	10	Adapted bacteria, 9 K medium, one step, initial pH 2	Rezaei et al. (2018)

**MPTS* mobile phone touch screen

Moreover, several specific features were observed when bacteria were used. For example, *A. thiooxidans* has been found to secrete organic compounds, some initially identified as polypeptides and amino acids, and others as metabolites such as phosphatidylinositol. This compound evidently enhances elemental sulfur oxidation by acting as a wetting agent, which can significantly affect bioleaching efficiency (Bobadilla Fazzini et al. 2011).

b) Application of heterotrophic microorganisms.

In studies by Cui et al. (2021, 2020), the heterotrophic microscopic fungi *Aspergillus niger* was used to recover In from LCD monitors. The fermentation broth obtained after 15 days of cultivation was used as the bioleaching agent, eliminating the need for direct contact between the ITO powder and fungi. Upon addition of the broth, 100% of In was recovered within 90 min at 70 °C. Bioleaching with *A. niger* did not alter the crystal or surface structure of ITO glass powder, unlike leaching with strong inorganic acids. Therefore, the glass residues from fermentation broth bioleaching could potentially be reused as raw materials for LCD production. The addition of low concentration of oxalic acid (0.5 M) during bioleaching simulations also resulted in very high In leaching efficiency (100%). Another available study applying bioleaching by heterotrophic bacteria was conducted by Golzar-Ahmadi and Mousavi (2021). They extracted Ag, Mo, and Cu with efficiencies of 100%, 57%, and 41%, respectively, over 12 days using organic acids produced by *Bacillus foraminis*.

c) Hybrid bioleaching combining autotrophic and heterotrophic microorganisms.

In hybrid bioleaching, authotrophic and heterotrophic microorganisms were combined to bioleach metals from LED displays. In the first step, biogenic ferric iron produced by *A. ferrooxidans* was used over a period of 10 days. In the subsequent second step, spent medium containing glycine and methionine, produced by *Bacillus megaterium.* was applied, lasting 4 days. Metals such as Sn, Ni, Cu, Al, Ga, Pb, Cr, and Fe were dissolved during the first step. In the following heterotrophic bioleaching by *B. megaterium*, the remaining Ni, Cu and Ga, along with 93% of Au and 91% of Ag, were recovered (Pourhossein et al. 2021).

The main challenges facing the further development of biometallurgical methods for FPD treatment can be grouped into three categories (Fig. 6):

- Industrial scale: most biometallurgical research is conducted at the laboratory scale, and further research and optimization are needed to scale up these methods for industrial application.
- Process time: biometallurgical processes are usually slower than traditional chemical methods, which may limit their efficiency in industrial settings.
- Material complexity: FPD contain a mixture of various materials and metals, making the selective recovery of In and other metals using microorganisms more difficult.

However, there are promising solutions and rapidly developing trends that may accelerate the implementation of green technologies in FPD recycling. These include: a) the development of hybrid approaches and the integration of biometallurgy with other techniques, such as mechanical or chemical preconcentration, to enhance the efficiency of metal recovery; b) research on microorganisms through genetic engineering, which could enable the development of strains optimized for the selective recovery of metals; c) collaboration with industry and the establishment of pilot recycling plants utilizing biometallurgy to evaluate the practical effectiveness of these methods.

3.3 Metal recovery from generated solutions

3.3.1 Chemical methods

Solvent extraction plays an important role in the recovery of metals from diluted solutions. This technique involves using organic solvents to selectively strip target metals from aqueous solutions. It is based on the different solubilities of metals in two immiscible liquids, typically an aqueous solution (polar) and an organic solvent (non-polar). In the study by Pereira et al. (2018), solvent extraction using 30% di-(2-ethylhexyl)phosphoric acid (D2EHPA) resulted in a final In concentration after stripping that was 236 times higher than the initial concentration, i.e. 7712 mg/L. Organophosphate compounds such as Cyanex 272 (Gupta et al. 2007), bis-2,2-ethylhexyl phosphate (DEHPA) (Virolainen et al. 2011; Yang et al. 2013), 2-ethylhexyl phosphonic mono-2-ethylhexyl ester (Kang et al. 2011), and a mixture of four trialkyl phosphates (Cynaex 923) (Sato and Sato 1992) have also been tested for In extraction, especially in earlier studies. Except from Cyanex 272, all other extractants were found to selectively extract In from acidic chloride or sulfate media (Yang et al. 2016). Fontana et al. (2015) employed an aqueous biphasic system (ABS) for In extraction. Using a PEG–$(NH_4)_2SO_4$–H_2O system and 1,10-phenantroline as a ligand for In-ions, In was extracted from a 6 mol/L HCl solution. It was found that 80–95% of In could be recovered in the "bottom phase" of the ABS, with a 30% (110 ppm) increase in In concentration compared to the initial concentration before extraction (85 ppm). According to De la Torre et al. (2018), the solution obtained after solvent extraction and stripping was evaporated, and In was precipitated with a 95% yield. The resulting indium sulfate was subsequently calcined at 700 °C for 2 h to produce the corresponding oxide.

After leaching, solvent extraction plays a critical role in separating REEs. Gergoric et al. (2017)

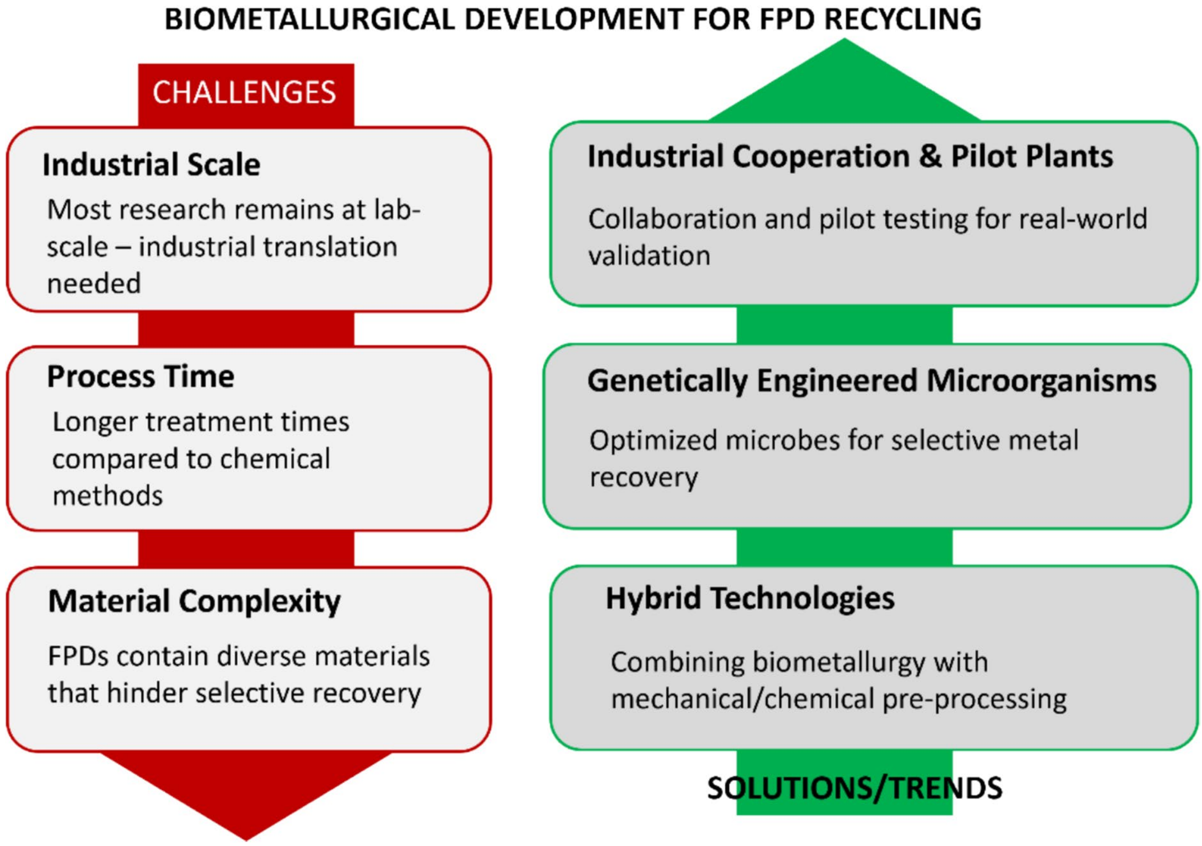

Fig. 6 Summarization of main challenges and possible solutions in the application of biometallurgy in FPD treatment

demonstrated that 0.3 M D2EHPA in hexane provided high separation factors between heavy and light REEs, with no extraction of B or Co. Complete REE extraction was achieved using 0.9–1.2 M D2EHPA in hexane or octane. Aliphatic diluents proved more effective than aromatic ones, and efficient metal stripping was achieved with ≥ 2 M HCl. Additionally, the application of D2EHPA for In extraction has been optimized by Yang et al. (2014), where the solvent extraction process was tailored to maximize yield from initial leaching operations. This approach demonstrates that solvent extraction can recover not only In but also other co-leached metals. In addition to In, tin (Sn) represents another valuable metal for recovery from ITO-coated LCD screens, where it is present mainly as SnO_2 (~ 10 wt%). Several hydrometallurgical studies have demonstrated effective strategies for tin extraction and separation. Souada et al. (2018) showed that ultrasound-assisted sulfuric acid leaching enables rapid and almost quantitative dissolution of the ITO layer. At 60 °C with 18 mol/L H_2SO_4, nearly 100% In yield and high dissolution efficiency of tin were achieved within only 3–4 min, whereas in the absence of ultrasound, the recovery was limited to about 70%. A more recent study by Qin et al. (2023) optimized the leaching of tin from mechanically activated ITO glass. Using a Box–Behnken experimental design, the maximum tin recovery of 87.6% was obtained under optimal conditions (6 mol/L H_2SO_4, 108 min, 88 °C, particle size 0.035 mm). The authors also confirmed that mechanical activation improves the reactivity of the glass surface and facilitates the release of Sn^{4+} ions into the leachate. However, selective leaching strategies can be employed to separate In from tin during the leaching stage itself. Xu et al. (2024) proposed a process for selective leaching of In from ITO using H_2SO_4 in the presence of H_2O_2. Under optimal conditions (H_2SO_4 concentration of 2.0 mol/L, L/S ratio of 4.0 mL/g, temperature of 80 °C, time of 5 h), In_2O_3 was effectively dissolved, while most of the tin remained in the leach residue in the form of H_2SO_4-stable SnO_2. The addition of H_2O_2 during acid leaching oxidized tin from valence state + 2 to + 4, thereby forming H_2SO_4-stable SnO_2, which limited the co-dissolution of tin with In. The tin leaching efficiency decreased with increasing H_2O_2 dosage.

Cementation is another method used to separate metal ions in aqueous solutions based on differences in electrochemical potential. Rocchetti et al. (2016) studied In extraction by cementation from sulfate solutions using Zn powder (2–100 g/L of Zn). Almost all In transferred to the solid phase at pH 3 within 10 min. The final purity was 62%, although the presence of major impurities (i.e., Al, Ca, and Fe) increased with longer cementation times. Li et al. (2011) developed a comprehensive hydrometallurgical process that combines acid leaching, removal of tin from the leach solution by sulfide precipitation, and deposition of sponge In by zinc cementation. During leaching with an initial concentration of 100 g/L H_2SO_4 at 90 °C for 2 h, 99% of In was leached, while only approximately 8% of tin was dissolved (Li et al. 2011). Tin in the leach solution was subsequently reduced to 10 mg/L by sulfide precipitation under H_2S partial pressure of 101.3 kPa and 100 g/L H_2SO_4 at 60 °C for 10 min, with indium loss being less than 1%. Chemical analysis of the sulfide residue showed tin content (as SnO_2 and SnS) of 66.17% and remaining In of 3.11%, with tin removal and In loss calculated at 100% and 0.47%, respectively.

Precipitation of In from LCDs as In hydroxide is also a viable alternative. Silveira et al. (2015) achieved 99.8 wt% In precipitation at pH 7.4 using ammonium hydroxide (NH_4OH). However, other elements (e.g., aluminum) with similar properties to In may co-precipitate, which is a drawback of this method (Zheng et al. 2023).

Another promising alternative to traditional organic solvents in the extraction phase is the use of ionic liquids (ILs), which are non-flammable and non-volatile (e.g. Deferm et al. 2016; Alguacil and López 2020). However, ILs have some disadvantages, such as high cost and high viscosity, which can lead to slow mass transfer and prolonged contact times to reach equilibrium (Fontana et al. 2020). For example, Cyphos IL104 phosphonium ionic liquid, diluted in toluene, achieved 98.9% In recovery from LCD leachate (Dhiman and Gupta 2020), while betainium bis(tri fluoromethylsulfonyl) imide ([Hbet][Tf2N]) yielded 98.6% recovery (Luo et al. 2019).

Electrochemical separation (electrowinning), although rarely reported, is another potential technique for recovering In from LCDs. Its effectiveness depends on factors such as electrolyte composition and the presence of complexing agents in leachates (Grimes et al. 2017). Choi et al. (2014) used an electrochemical technique to recover ITO from obsolete TFT-LCD panels but found that the In could not be reused directly due to an unsuitable ratio of In and Sn. Conversely, the use of a three-stage cylindrical mesh electrode electrolysis system is a promising technology for the recovery of In from LCDs, achieving a 98% total In recovery (Grimes et al. 2017). Xu et al. (2023) proposed an efficient method for waste ITO target recycling based on electro-deoxidation in molten chlorides. Thermodynamic analysis showed a wide potential window of 2.26 V for the co-reduction of In_2O_3 and SnO_2 at 750 °C in the molten NaCl-KCl system. After 3.0 h of electrolysis at a constant cell voltage of 3.0 V, the waste ITO target was completely reduced to the corresponding metallic products, with recovery percentages of tin reaching 92.6%. In case of supercritical fluid separation, the optimal recovery conditions were found to be a temperature of 300 °C and a water content of 60% in the water–ethanol mixture, allowing for 85.7% In recovery in just 4 h (Argenta et al. 2017). Extraction methods and conditions reported by various authors, including some of those mentioned above, are summarized by Zheng et al. (2023). A less detailed comparison was also presented by Zhang et al. (2020).

Furthermore, advanced techniques such as membrane filtration offer enhanced metal ion concentration from leachates, setting the stage for more efficient subsequent extraction processes, as examined by Lahti et al. (2020). The integration of adsorption technologies, using materials like functionalized chitosan for the selective binding of metal ions, can further enhance recovery of a wide range of elements present in LCD screens.

In conclusion, the chemical extraction of metals from leachate solutions generated during the recycling of LCD screens involves a comprehensive suite of processes, ranging from acidic leaching and solvent extraction to innovative biotechnological approaches. Each method holds potential for the recovery of metals such as In and other REEs, thereby contributing to a more effective recycling framework that addresses the urgent need for sustainable metal recovery from e-waste.

3.3.2 Biological methods

3.3.2.1 Biosorption and Bioaccumulation One of the biological routes for recovering In and other metals from leachates following the FPD leaching process is the use of biosorption or bioaccumulation. The key difference between these two processes lies in their underlying mechanisms. While biosorption involves the adsorption of metal ions onto the surface of the biomass, bioaccumulation primarily entails the accumulation of metal ions within the cells (Fig. 7).

Bioaccumulation often occurs in two steps: a rapid initial step in which metal ions adsorb onto the biomass surface (similar to biosorption), followed by a slower transport step into the cell. Biosorption is a metabolism-independent process that is fast and reversible, usually with a higher capacity compared to bioaccumulation. In contrast, bioaccumulation is slow, metabolism-dependent, and thus energy-requiring, with a capacity that typically represents only 0.5–2% of the dry cell weight. However, from a technological perspective, simpler definitions are often used: biosorption refers to processes involving nonliving biomass, while bioaccumulation applies to living cells (Kaduková and Vircíková 2005; Sedlakova-Kadukova 2022).

Several studies have applied biosorption/bioaccumulation to recover In, Sn and other metals from solution, however, model solutions are predominantly used. Very high bioaccumulation rates were observed for the Gram-negative bacterium *Shewanella algae*. Ogi et al. (2012) found that this bacterium was able to accumulate 100% and 54% of In from $InCl_3$ model solutions with initial concentrations of 11.4 and 107.2 mg/l, respectively, at pH values between 2.3 and 3.9. After drying the In-loaded bacterial biomass (from the highest tested In initial concentration of 107.2 mg/l), they obtained dried biomass containing approximately 5.4% (w/w) In, which was 474 times higher than the In concentration in the initial solution. Subsequent heating of the biomass at approximately 800 °C for 2 h yielded a powder containing 40% In (w/w), which is 4300 times the concentration of In(III) in the initial solution. The authors did not

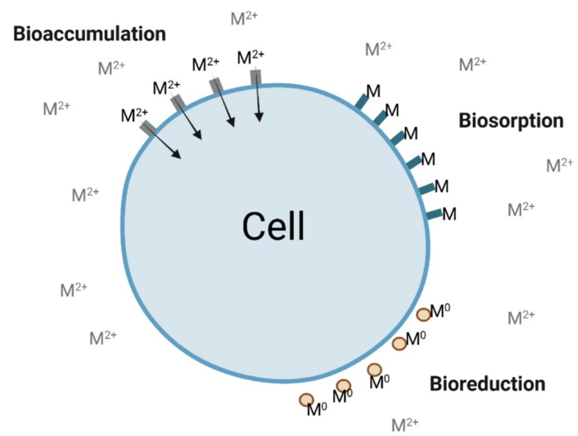

Fig. 7 Comparison of basic characteristics of three biological processes suitable for recovery of In and other metals from leachates after FPD leaching (M; symbol for metal)

observe the reduction of In(III) to In(0). Similarly, Saitoh et al. (2017) observed high (100%) bioaccumulation of In by *S. algae* biomass from synthetic solution with an initial concentration of 100 mg/L at pH values ranging from 2.3 to 3.5. High In recovery was also reported for the psychrophilic yeast strain *Cryptococcus laurentii* (Rusinova-Videva et al. 2020). The authors studied the bioaccumulation of various metals from synthetic solutions with initial concentrations of 20 mg/L, achieving recovery in the range of 12–16 mg/g of dry biomass at an optimal pH of 5. Although most studies have used $InCl_3$ model solutions to study In recovery, Saitoh et al. (2017) found that the bacterium *S. algae* exhibits high selectivity for collecting In from leachate obtained by leaching LCD monitors with dilute HCl solution. Similarly, Maeda et al. (2022) confirmed the high selectivity of *S. algae* for In recovery from spent LCD monitor leachate via pH adjustment. The only study reporting tin bioaccumulation investigated the utilisation of the living biomass of cyanobacterium *Spirulina platensis* for the biotemplated synthesis of functional materials (Tao et al. 2014). Although the authors did not directly address bioaccumulation or biosorption, their results provide evidence of tin sequestration on the *Spirulina* surface through the complexation of Sn^{4+} ions with hydroxyl groups associated with alginate.

Biosorption studies using non-living biomass for In recovery from solutions is very rare. Pennesi et al. (2019) studied In biosorption using biomass from the brown alga *Ascophyllum nodosum*, examining both naturally occurring biomass and waste products from biomass processing in biostimulant production. They found that In biosorption is pH-dependent, with an optimum at pH 3. The maximum biosorption capacity was found to be 48 mg/g for the processed waste biomass and 63 mg/g for the natural biomass. Acid-pretreated and urea-modified wheat straw have been investigated for their tin biosorption capacity. The maximum sorption capacities, calculated using the Langmuir isotherm model, were 47.8 and 64.1 mg/g for the respective materials (Raza et al. 2014).

3.3.2.2 Bioreduction and production of nanoparticles Another biological approach suitable for the recovery of In and other metals from FPD leachate is bioreduction. Bioreduction is one of the bioprecipitation mechanisms that leads to the reduction of metallic ions, often forming solid particles. In general, solid precipitates form on the surface of microorganisms or in solution, based on the interaction between organisms and metals (Fig. 7) (Sedlakova-Kadukova 2022). However, in specific cases where bioactive compounds capable of acting as capping agents are present (sometimes the same molecules responsible for reduction), nanoparticles are formed (Kadukova 2016). Biological methods of nanoparticle formation have been summarized in various review articles (e.g. Villagrán et al. 2024; Cardoso et al. 2025; Bokolia et al. 2025); therefore, it is not the aim of the present paper to review them.

Biological methods can result in the formation of several types of In, Sn or other metals containing nanoparticles. In biosynthetic processes, the formation of multiple nanoparticle types is commonly observed rather than the production of a single, uniform type. For instance, in the case of In, at least three distinct types of In-containing nanoparticles have been reported. The first type is indium oxide (In_2O_3) nanoparticles, which have received significant attention due to their unique properties, such as high conductivity, stability at elevated temperatures, and strong interactions with target gases including ethanol, ammonia, and carbon monoxide. Their formation has been demonstrated using various plant extracts, such as *Aloe vera* (Kulkarni et al. 2024), *Boerhavia diffusa* (Rozina et al. 2023), and *Aerva javanica* (Ali et al. 2023). Another type of In-containing nanoparticles is the sulfide form. Leaves of *Mimosa pudica* served as a template in a hydrothermal method for the production of biomimetic sulfur-deficient indium sulfide (In_2S_3) nanoparticles by Carrasco-Jaim et al. (2019), which were applied in photocatalytic hydrogen production. Another suitable reagent for $In_{2.77}S_4$ nanoparticle preparation was castor oil, used in a microwave-assisted process (Lethukuthula et al. 2023). A large group of In-containing nanoparticles comprises complex alloys or composites, such as $AgInSe_2$ produced by *Pseudomonas aeruginosa* (Çakıcı et al. 2023), In_2O_3-SnO_2 synthesized using acacia gum (Shanti Sree et al. 2019), Cu-In-S produced by Antarctic yeast *Filobasidium stepposum* (Arriaza-Echanes et al. 2024), and $InSnO_2$ synthesized using toddy palm from *Borassus flabellifer* (Merugu and Gothalwal 2021) or almond gum (Shanti Sree et al. 2021).

In the case of tin bioreduction and nanoparticle synthesis, a variety of organisms and their extracts can act as both reducing and stabilizing agents. For example, extracts of *Garcinia cambogia* (Jafeesh et al. 2023), jujube fruit (*Ziziphus jujuba*) (Honarmand et al. 2019), kabuli chickpea seeds (*Cicer arietinum*) (Kundu et al. 2020), and *Terminalia chebula* seeds (Gautam et al. 2024) have been employed for the biosynthesis of SnO_2 nanoparticles. Furthermore, SnO_2, silver–tin oxide (Ag–SnO_2), and Ag–Bi–SnO_2 nanoparticles have been synthesized using methanolic seed extracts of *Caesalpinia bonduc* (Siddique et al. 2022). The use of various biological extracts in tin nanoparticle synthesis has been comprehensively reviewed in previous studies (e.g., Ahmad et al. 2021). SnO_2 nanoparticles exhibit enhanced photocatalytic, antioxidant, and antimicrobial activities and have been successfully applied in the photocatalytic degradation of organic dyes, the suppression of pathogenic fungi in agricultural crops, and the fabrication of various sensors.

Based on recent findings, biological routes show great promise for a variety of applications compared to traditional nanoparticle production methods, and this is not solely due to their environmentally friendly nature. Although direct comparisons between the effects of biologically and chemically or physically produced nanoparticles are still rare in the scientific literature, some relevant studies do exist. Several authors have reported that biologically prepared silver (Ag) nanoparticles exhibit different biological effects compared to chemically prepared ones. For example, when biologically prepared nanoparticles were applied to soil ecosystems, they triggered very low to negligible levels of antibiotic resistance in soil bacteria, in contrast to chemically prepared nanoparticles or ionic Ag forms (Sedlakova-Kadukova et al. 2025). Similarly, different effects were observed on the immune system (Demeckova et al. 2025). Improved characteristics have also been reported for biologically produced In-containing nanoparticles. Kulkarni et al. (2024) found that the electrical sensitivity of gas sensors containing biologically produced In_2O_3 nanoparticles was significantly higher compared to those produced by traditional synthesis methods. Likewise, Carrasco-Jaim et al. (2019) reported threefold higher photocatalytic hydrogen production rates for indium sulfide nanoparticles synthesized with biological agents compared to those synthesized without them. In case of tin containing nanoparticles, Kundu et al. (2020) reported superior CO sensing performance of biosynthesized SnO_2 nanoparticles compared to sol–gel- or sonochemically-derived tin oxides operating under similar conditions.

Bioreduction thus represents a promising biological approach for the recovery of In and other metals from FPD leachate. It is capable of producing various types of In-containing nanoparticles (oxides, sulfides, and complex alloys), which often exhibit superior properties compared to those synthesized through conventional methods.

4 Analytical challenges

Metal analysis in FPD is essential for understanding the composition and performance of the materials used in their fabrication. Analyzing the metallic elements in these displays supports quality control, failure analysis, and ensures product reliability. Detecting trace amounts of metals such as In, Sn, Ag, or Cu requires highly sensitive instruments. Solutions for this application include techniques such as ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry), which are commonly used to detect trace metals. However, achieving the required sensitivity and accuracy remains a challenge due to potential matrix effects or contamination. Among the methods of atomic spectrometry, ICP-OES (Profumo et al. 2008; Cummings et al. 2016; Hu et al. 2021) and ICP-MS (Su et al. 2018; Werner et al. 2019) are the most frequently used techniques for the quantitative analysis of technology-critical elements.

X-ray Fluorescence (XRF) Spectroscopy is a non-destructive technique widely used in FPD manufacturing to quickly assess the elemental composition of thin metal layers. Another useful technique is Auger Electron Spectroscopy (AES), a surface-sensitive method that provides information about the elemental composition of the outermost atomic layers of the FPD. Electron Probe Micro-Analysis (EPMA), an electron microscopy-based technique, is used for the quantitative analysis of metallic elements in FPD. Another highly sensitive technique is Secondary Ion Mass Spectrometry (SIMS), widely used in metal analysis of FPD due to its surface sensitivity. Glow Discharge Optical Emission Spectroscopy (GDOES) is particularly useful for analyzing thin metal coatings or films in FPD, as it provides depth profiles of metal layers. Energy Dispersive X-ray Spectroscopy (EDS) provides both qualitative and semi-quantitative data and is capable of analyzing small areas, making it ideal for defect analysis. EDS is often coupled with Scanning Electron Microscopy (SEM) for elemental analysis (Wang et al. 2014; Cho and Kim 2024). When the FPD sample is scanned with an electron beam, the emitted X-rays are characteristic of the elements in the sample. EDS is typically used for local metal analysis in FPD, especially for examining defects or specific areas of interest.

Time-of-Flight Secondary Ion Mass Spectrometry (TOF–SIMS) can analyze very small areas, down to the nanoscale. As a variation of SIMS, TOF–SIMS provides mass analysis of secondary ions based on their time-of-flight, allowing for very high mass resolution and sensitivity. This technique is particularly valuable for analyzing the distribution of metals and organic materials in FPD at the nanoscale. Atomic Absorption Spectroscopy (AAS) is a method often used to detect specific metal elements by measuring the absorption of light by free atoms. This technique is precise and accurate for certain metals, and is especially effective for measuring elements like Pb, Hg, and other heavy metals that may be present as contaminants or in specific FPD components. While less commonly used than other advanced techniques, AAS remains valuable for its simplicity, precision and cost-effectiveness in routine analysis.

Laser-induced breakdown spectroscopy (LIBS) is useful for analyzing LCD pellet samples from mobile

Table 8 Analytical techniques used in quantitative FPD analyses

Elements	FPD type	Analytical technique	Reagents used for digestion	Source
Cd, Pb, Hg, Cr, Ni, Cu, Zn, As, Sn, Al, Fe	LCD	ICP-MS	100 mg of sample, 10 mL of mixed HNO_3 and HCl and at a ratio of 1:5	Savvilotidou et al. (2014)
Te, Ge, Tl, Cd, Ba, Co, Mn, Cr, Cu, Ni, Pb, Sr, Zn	LCD, LED,	ICP-MS	Aqua Regia	Willner et al. (2021)
Al, As, In, Sr, Ba, Ca, Si	LCD	ICP-OES	0.25 g of sample, mixture of HNO_3/HClO4/HF/HCl	Parsa et al. (2024)
In	LCD	LIBS, ICP-OES	0.20 g of sample, 5 mL of 65% HNO_3 and 2 mL of 40% HF	Andrade et al. (2019)
Al, Zn, Cu, As, Mo, Ag, In, Sn, Fe	LCD	ICP-MS	Aqua Regia	Schuster and Ebin (2021)
In, Sn, Si	LCD	ICP-AES	H_2SO_4	Souada et al. (2018)
C, N, O, In, Sn, Al	OLED	EDX	-	Filella and Rodushkin (2018)
In Sn Al Fe Cr Ni Zn	LCD	ICP-OES	100 g of the prepared LCD glass granules in 100 cm^3 12 M HCl at 90 ◦C	Cho and Kim (2024)
Pd, Pt, Au, Ge, Co, Ta, Ag, W, In, Mg, Nb,Y	LCD	XRF	-	Charles et al. (2020)
Y	LCD	ICP-MS	Digest phosphor in 1:1 HCl acid volume/sample mass ratio of 40 ml/g	Charles et al. (2020)

phones to determine In content, with detection limits ranging from 0.3 to 0.5 mg/kg (Andrade et al. 2019). Table 8 presents the most commonly used analytical techniques for the determination of metals in FPD.

Metal analysis in FPD presents numerous analytical challenges due to the need for high sensitivity, accuracy, and spatial resolution, combined with the complexity of multilayered materials. FPD consist of complex multilayer materials, including glass, polymers, organic compounds, and various thin metal films (Parsa et al. 2024). One of the main problems in analyzing such complex materials is matrix interference. Matrix effects, where one component in a sample interferes with the analysis of another, make it difficult to measure specific metals accurately. To overcome this, advanced matrix-matched standards or internal standards are used to correct for matrix effects on measurement accuracy, particularly in ICP-MS or XRF (X-ray fluorescence) analyses. The use of certified reference materials further helps validate and verify the accuracy of the results.

Another challenge in FPD analysis is the characterization of thin films and nanomaterials used in these devices (Charles et al. 2020). Modern FPD incorporate ultra-thin layers of metals, often on the nanometer scale, such as ITO layers in LCDs or thin Ag layers in OLEDs. Analyzing these thin films, especially their thickness and uniformity, without damaging the sample is particularly difficult. This often necessitates mechanical or chemical separation of the relevant material layers. Techniques such as X-ray Photoelectron Spectroscopy (XPS) and Secondary Ion Mass Spectrometry (SIMS) are commonly used for surface and thin-film analysis; however, precise control during these procedures is essential to avoid altering the metal layers. Sample preparation for metal analysis in FPD is also a significant challenge due to the diversity of materials involved (organic, inorganic, and metals) and the structural complexity of the displays. Cutting, dissolving, or otherwise preparing these layers for analysis, without losing metals or altering their state, can be problematic.

All analytical techniques have inherent limitations, particularly with respect to elemental interference and overlap. Some metals used in FPD produce overlapping spectral lines or signals in techniques like XRF or ICP-OES (Optical Emission Spectroscopy), complicating accurate elemental identification. In ICP-MS, analysts must also consider isobaric interferences, particularly those associated with the argon carrier gas. These interferences are often mitigated using a collision or reaction chamber. Although high-resolution instruments and deconvolution algorithms can help resolve overlapping peaks, the complexity of the resulting spectra remains a challenge.

When determining elemental content at the ultra-trace levels, stringent conditions are required. Contamination during sample preparation or analysis can significantly skew results, especially in the sensitive environment of FPD manufacturing, where strict cleanroom conditions are standard. Even trace contamination from metals in the laboratory environment can distort outcomes. Therefore, working in clean environments and employing specialized sample preparation techniques, such as acid cleaning or dry etching, can help minimize contamination. However, controlling all potential sources of contamination remains difficult.

In some cases, only specific regions of a display need to be analyzed for metal content, such as when detecting localized impurities or assessing the uniformity of metal distribution. Achieving high spatial resolution in such cases is challenging. Techniques like Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM–EDX) provide high spatial resolution but may lack the sensitivity required for trace-level analysis, leading to trade-offs.

5 Conclusions

The increasing demand for FPD in consumer electronics, coupled with their complex material composition, presents significant challenges for the recycling and recovery of valuable elements. Future EU actions should focus on increasing the efficiency of FPD collection and improving the monitoring of these waste streams to reduce In dispersion and enhance the availability of secondary raw materials. In parallel, it is crucial to develop and implement dedicated, scalable technologies for In recovery from ITO layers, which will enable genuine closure of the In cycle and reduce the EU's dependence on primary imports. Effective study of FPD recycling also relies on advances in analytical chemistry, with a need to develop faster, greener, and more selective methods for identifying and quantifying critical and hazardous elements. Regarding recycling technology, the future viability of In recovery from FPD depends on the development of optimized and selective pretreatment strategies that offset higher upfront costs by effectively concentrating In, reducing process volumes, and enabling economically scalable recovery routes. Existing pretreatment methods suffer from several disadvantages, such as particle agglomeration and toxic compound production. Magnetic pretreatment appears promising, as In accumulates in the ferromagnetic fraction bound to Fe-containing materials. Efficient pretreatment combined with hydro- or biometallurgical processes shows the greatest promise, as these approaches reduce waste volume, increase process selectivity and purity of the products. Biometallurgical methods themselves, including bioleaching for In dissolution, biosorption for selective recovery from solution, and bioreduction for nanoparticle production, offer an efficient and environmentally friendly basis for future technology. The future of FPD recycling lies in the development of scalable, low-energy, and selective processes applicable to diverse material streams. Biological methods, due to their flexibility and lower ecological footprint, hold significant promise for next-generation recycling technologies and may play a key role in building a resilient, circular supply chain for critical materials. A particularly promising yet underexplored area is the microbial degradation of organic components in FPD. Displays contain complex organic molecules designed for durability, yet their environmental fate remains poorly understood. Understanding microbial interactions with these materials can bridge a clear gap between materials science and environmental microbiology, supporting more sustainable and circular display recycling technologies. This is especially important as the goal extends far beyond degradation to converting organic components into useful products such as platform chemicals, bio-based additives, or precursors for new materials. Such approaches could improve end-of-life management of electronic waste while reducing reliance on virgin resources and helping to assess environmental and toxicity risks associated with transformation products.

Acknowledgements This work was supported by the Interreg Danube Region Programme co-funded by the European Union within project BioPrep (Biotechnological Innovations for Sustainable FPDs Recycling).

Author contributions Writing—original draft: JSK, JW, JT, VP, MJC, IJ; Writing—Reviewing & Editing: JSK, JW, JT, VP, MJC, IJ; Project administration: JSK, JW, JT, VP, MJC, IJ; Funding acquisition: JSK, IJ, JT. All authors have read and agreed to the submitted version of the manuscript.

Funding Open access publishing was supported by the University of Ljubljana, Slovenia.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interests.

References

Abhilash HS, Meshram P et al (2022) Extraction of REEs from blast furnace slag by gluconobacter oxydans. Minerals 12:701. https://doi.org/10.3390/min12060701

Pennesi C, Amato, A, Occhialini S, et al (2019) Adsorption of indium by waste biomass of brown alga Ascophyllum nodosum | Scientific Reports. Sci Rep 9.

Ahmad W, Pandey A, Rajput V et al (2021) Plant extract mediated cost-effective tin oxide nanoparticles: A review on synthesis, properties, and potential applications. Curr Res Green Sustain Chem 4:100211. https://doi.org/10.1016/j.crgsc.2021.100211

Akiyama E, Miyama Y, Nagase Y et al (2000) Novel photoinduced alignment phenomenon of liquid crystals on aromatic polyamide films. J Soc Inf Disp 8:259–267. https://doi.org/10.1889/1.1828761

Alam MJ, Cameron DC (2001) Characterization of transparent conductive ITO thin films deposited on titanium dioxide film by a sol–gel process. Surf Coat Technol 142:776–780. https://doi.org/10.1016/S0257-8972(01)01183-5

Alguacil FJ, López FA (2020) Dispersion-free extraction of In(III) from HCl solutions using a supported liquid membrane containing the HA324H+Cl− ionic liquid as the carrier. Sci Rep 10:13868. https://doi.org/10.1038/s41598-020-70968-1

Ali SS, Elsamahy T, Al-Tohamy R et al (2021) Plastic wastes biodegradation: mechanisms, challenges and future prospects. Sci Total Environ 780:146590. https://doi.org/10.1016/j.scitotenv.2021.146590

Ali Z, Aadil M, zainab B et al (2023) Synthesis of nanostructured In2O3 ceramics via a green and chemical method for the mineralization of crystal violet dye: A comparative study. Inorg Chem Commun 157:111399. https://doi.org/10.1016/j.inoche.2023.111399

Altarawneh M, Saeed A, Al-Harahsheh M, Dlugogorski BZ (2019) Thermal decomposition of brominated flame retardants (BFRs): products and mechanisms. Prog Energy Combust Sci 70:212–259. https://doi.org/10.1016/j.pecs.2018.10.004

Amato A, Beolchini F (2018) End of life liquid crystal displays recycling: a patent review. J Environ Manage 225:1–9. https://doi.org/10.1016/j.jenvman.2018.07.035

Amato A, Rocchetti L, Beolchini F (2017) Environmental impact assessment of different end-of-life LCD management strategies. Waste Manag 59:432–441. https://doi.org/10.1016/j.wasman.2016.09.024

Ammala A, Bateman S, Dean K et al (2011) An overview of degradable and biodegradable polyolefins. Prog Polym Sci 36:1015–1049. https://doi.org/10.1016/j.progpolymsci.2010.12.002

Anandan M (2008) Progress of LED backlights for LCDs. J Soc Inf Disp 16:287–310. https://doi.org/10.1889/1.2841864

Andrade DF, Fortunato FM, Pereira-Filho ER (2019) Calibration strategies for determination of the In content in discarded liquid crystal displays (LCD) from mobile phones using laser-induced breakdown spectroscopy (LIBS). Anal Chim Acta 1061:42–49. https://doi.org/10.1016/j.aca.2019.02.038

Ardente F, Mathieux F, Recchioni M (2014) Recycling of electronic displays: analysis of pre-processing and potential ecodesign improvements. Resour Conserv Recycl 92:158–171. https://doi.org/10.1016/j.resconrec.2014.09.005

Argenta AB, Reis CM, Mello GP et al (2017) Supercritical CO2 extraction of indium present in liquid crystal displays from discarded cell phones using organic acids. J Supercrit Fluids 120:95–101. https://doi.org/10.1016/j.supflu.2016.10.014

Arriaza-Echanes C, Campo-Giraldo JL, Valenzuela-Ibaceta F et al (2024) Biosynthesis of Cu-In-S nanoparticles by a yeast isolated from Union Glacier, Antarctica: a platform for enhanced quantum dot-sensitized solar cells. Nanomaterials 14:552. https://doi.org/10.3390/nano14060552

Aston JE, Thompson VS, Fujita Y, Reed DW (2022) Metabolic flux modeling of *Gluconobacter oxydans* enables improved production of bioleaching organic acids. Process Biochem 122:350–356. https://doi.org/10.1016/j.procbio.2022.10.027

Bavarva A, Bavarva T (2018) (PDF) QLED and IGZO: The Future of Television Display Technology. Electron. You

Becci A, Amato A, Merli G, Beolchini F (2024) The green Indium patented technology SCRIPT, for Indium recovery from liquid crystal displays: bench scale validation driven by sustainability assessment. Sustainability 16:8917. https://doi.org/10.3390/su16208917

Beeler SR, Rehwinkel EA, Carlson BN (2024) Bioleaching of Manganese from Ferromanganese nodules utilizing acetogenic bacteria in a symbiotic community of bacteria and yeast. J Sustain Metall 10:2376–2383. https://doi.org/10.1007/s40831-024-00945-9

Bellenberg S, Turner S, Seidel L et al (2021) Towards bioleaching of a Vanadium containing magnetite for metal recovery. Front Microbiol. https://doi.org/10.3389/fmicb.2021.693615

Bettencourt AF, Neves CB, de Almeida MS et al (2010) Biodegradation of acrylic based resins: a review. Dent Mater 26:e171–e180. https://doi.org/10.1016/j.dental.2010.01.006

Bobadilla Fazzini RA, Levican G, Parada P (2011) *Acidithiobacillus thiooxidans* secretome containing a newly described lipoprotein Licanantase enhances chalcopyrite bioleaching rate. Appl Microbiol Biotechnol 89:771–780. https://doi.org/10.1007/s00253-010-3063-8

Bokolia M, Baliyan D, Kumar A et al (2025) Biogenic synthesis of nanoparticles using microbes and plants: mechanisms and multifaceted applications. Int J Environ Anal Chem 105:2069–2097. https://doi.org/10.1080/03067319.2024.2305238

Borja J, Taleon DM, Auresenia J, Gallardo S (2005) Polychlorinated biphenyls and their biodegradation. Process Biochem 40:1999–2013. https://doi.org/10.1016/j.procbio.2004.08.006

Brierley CL (2008) How will biomining be applied in future? Trans Nonferrous Met Soc China 18:1302–1310. https://doi.org/10.1016/S1003-6326(09)60002-9

Çakıcı T, Ajjaq A, Çağırtekin AO et al (2023) Surface activation of Si-based Schottky diodes by bacterial biosynthesized AgInSe2 trimetallic alloy nanoparticles with evidenced negative capacitance and enhanced electrodielectric performance. Appl Surf Sci 631:157522. https://doi.org/10.1016/j.apsusc.2023.157522

Cao Y, Li F, Li G et al (2020) Leaching and purification of indium from waste liquid crystal display panel after hydrothermal pretreatment: optimum conditions determination and kinetic analysis. Waste Manag 102:635–644. https://doi.org/10.1016/j.wasman.2019.11.029

Cardoso B, Nobrega G, Afonso IS et al (2025) Sustainable green synthesis of metallic nanoparticle using plants and microorganisms: a review of biosynthesis methods, mechanisms, toxicity, and applications. J Environ Chem Eng 13:116921. https://doi.org/10.1016/j.jece.2025.116921

Carrasco-Jaim OA, Ahumada-Lazo R, Clark PCJ et al (2019) Photocatalytic hydrogen production by biomimetic indium sulfide using Mimosa pudica leaves as template. Int J Hydrog Energy 44:2770–2783. https://doi.org/10.1016/j.ijhydene.2018.12.043

Charles RG, Douglas P, Dowling M et al (2020) Towards increased recovery of critical raw materials from WEEE—evaluation of CRMs at a component level and pre-processing methods for interface optimisation with recovery processes. Resour Conserv Recycl 161:104923. https://doi.org/10.1016/j.resconrec.2020.104923

Chen D, Hale RC, Letcher RJ (2015) Photochemical and microbial transformation of emerging flame retardants: cause for concern? Environ Toxicol Chem 34:687–699. https://doi.org/10.1002/etc.2858

Cheng J, Li X, Yuan Y et al (2024) Environmental behavior, toxic potencies, and risks of liquid crystal monomers: a critical review. Crit Rev Environ Sci Technol. https://doi.org/10.1080/10643389.2024.2373948

Cho WJ, Kim MJ (2024) Study on characteristics of LCD glass powder and its effect on the chloride binding capacity. Constr Build Mater 444:137757. https://doi.org/10.1016/j.conbuildmat.2024.137757

Ciacci L, Werner TT, Vassura I, Passarini F (2019) Backlighting the European indium recycling potentials. J Ind Ecol 23:426–437. https://doi.org/10.1111/jiec.12744

Constantin A, Pourhossein F, Ray D, Farnaud S (2024) Investigating the acidophilic microbial community's adaptation for enhancement indium bioleaching from high pulp density shredded discarded LCD panels. J Environ Manage 365:121521. https://doi.org/10.1016/j.jenvman.2024.121521

Costa MR, Altafim RAC, Mammana AP (2003) Dielectric behavior of Polyvinyl alcohol (Pva) and its influence on Lcds. Mol Cryst Liq Cryst 393:49–55. https://doi.org/10.1080/10587250307073

Baldé CP, Kuehr R, Tales Yamamoto, et al (2024) The Global E-waste Monitor 2024, 1. International Telecommunication Union (ITU) and United Nations Institute for Training and Research (UNITAR), Geneva/Bonn

Battelle (2023) Critical material recovery from E-waste

Cui J, Zhu N, Luo D et al (2019) The role of oxalic acid in the leaching system for recovering indium from waste liquid crystal display panels. ACS Sustain Chem Eng 7:3849–3857. https://doi.org/10.1021/acssuschemeng.8b04756

Cui J, Zhu N, Li Y et al (2020) Rapid and green process for valuable materials recovery from waste liquid crystal displays. Resour Conserv Recycl 153:104544. https://doi.org/10.1016/j.resconrec.2019.104544

Cui J, Zhu N, Mao F et al (2021) Bioleaching of indium from waste LCD panels by Aspergillus niger: Method optimization and mechanism analysis. Sci Total Environ 790:148151. https://doi.org/10.1016/j.scitotenv.2021.148151

Cummings KJ, Virji MA, Park JY et al (2016) Respirable indium exposures, plasma indium, and respiratory health among indium-tin oxide (ITO) workers. Am J Ind Med 59:522–531. https://doi.org/10.1002/ajim.22585

Cuvilas CA, Yang W (2012) Spruce pretreatment for thermal application: water, alkaline, and diluted acid hydrolysis. Energy Fuels 26:6426–6431. https://doi.org/10.1021/ef301167v

Das HS, Nandi PK (2021) Organic Light Emitting Diode (OLED) technology and its applications: literature review. Open Conserv Biol J. https://doi.org/10.31031/BOJ.2021.02.000527

Das R, Das HS, Nandi PK, Biring S (2018) Comparative studies on the properties of magnetron sputtered transparent conductive oxide thin films for the application in solar cell. Appl Phys A 124(9):631

la De la Torre E, Vargas E, Ron C, Gámez S (2018) Europium, yttrium, and indium recovery from electronic wastes. Metals 8:777. https://doi.org/10.3390/met8100777

Deferm C, de Voorde MV, Luyten J et al (2016) Purification of indium by solvent extraction with undiluted ionic liquids. Green Chem 18:4116–4127. https://doi.org/10.1039/C6GC00586A

Demeckova V, Demeckova V, Sedlakova-Kadukova J (2025) Differences in immunological impact of chemically and biologically synthesized silver nanoparticles. IEEE Trans Nanobioscience. https://doi.org/10.1109/TNB.2025.3564822

Dodbiba G, Nagai H, Wang LP et al (2012) Leaching of indium from obsolete liquid crystal displays: comparing grinding with electrical disintegration in context of LCA. Waste Manag 32:1937–1944. https://doi.org/10.1016/j.wasman.2012.05.016

Dodson JR, Hunt AJ, Parker HL et al (2012) Elemental sustainability: towards the total recovery of scarce metals. Chem Eng Process 51:69–78. https://doi.org/10.1016/j.cep.2011.09.008

El-Gendi H, Taha TH, Ray JB, Saleh AK (2022) Recent advances in bacterial cellulose: a low-cost effective production media, optimization strategies and applications. Cellulose 29:7495–7533. https://doi.org/10.1007/s10570-022-04697-1

Eluri A, Gates WP, Callahan DL et al (2025) A pyrolysis gas chromatography high resolution mass spectrometry (Py-GC-MS) method for analysis of phthalic acid esters and its application for screening e-waste materials. Anal Methods 17:7409–7419. https://doi.org/10.1039/D5AY00987A

Etnews (2022) https://www.etnews.com

Ferella F, Belardi G, Marsilii A et al (2017) Separation and recovery of glass, plastic and indium from spent LCD panels. Waste Manag 60:569–581. https://doi.org/10.1016/j.wasman.2016.12.030

Field JA, Sierra-Alvarez R (2008) Microbial transformation and degradation of polychlorinated biphenyls. Environ Pollut 155(1):1–12. https://doi.org/10.1016/j.envpol.2007.10.016

Filella M, Rodushkin I (2018) A concise guide for the determination of less-studied technology-critical elements (Nb, Ta, Ga, In, Ge, Te) by inductively coupled plasma mass spectrometry in environmental samples. Spectrochim Acta B at Spectrosc 141:80–84. https://doi.org/10.1016/j.sab.2018.01.004

Fontana D, Forte F, De Carolis R, Grosso M (2015) Materials recovery from waste liquid crystal displays: a focus on indium. Waste Manag 45:325–333. https://doi.org/10.1016/j.wasman.2015.07.043

Fontana D, Forte F, Pietrantonio M, Pucciarmati (2020) Recent developments on recycling end-of-life flat panel displays: a comprehensive review focused on indium. Crit Rev Environ Sci Technol. https://doi.org/10.1080/10643389.2020.1729073

Forte F (2014) Materials recovery from waste liquid crystals displays: a focus on indium. (Doctoral Dissertation). Retrieved from https://www.politesi.polimi.it/handle/10589/99744

Fortin-Lecomte C, Tran L-H, Rioux G et al (2022) Recovery of indium from acidic leach solutions of spent LCD panels using ion exchange. Hydrometallurgy 210:105845. https://doi.org/10.1016/j.hydromet.2022.105845

Frenzel M, Mikolajczak C, Reuter MA, Gutzmer J (2017) Quantifying the relative availability of high-tech by-product metals—the cases of gallium, germanium and indium. Resour Policy 52:327–335. https://doi.org/10.1016/j.resourpol.2017.04.008

Furukawa K, Fujihara H (2008) Microbial degradation of polychlorinated biphenyls: biochemical and molecular features. J Biosci Bioeng 105:433–449. https://doi.org/10.1263/jbb.105.433

Gabriel AP, Kasper AC, Veit HM (2020) Acid leaching of indium from the screens of obsolete LCD monitors. J Environ Chem Eng 8:103758. https://doi.org/10.1016/j.jece.2020.103758

Gautam S, Tomar K, Singh Tomar A et al (2024) Eco-friendly synthesis of tin oxide nanoparticles: a novel strategy for managing early blight and soft rot in tomato crops. Inorg Chem Commun 169:113126. https://doi.org/10.1016/j.inoche.2024.113126

Gaytán I, Burelo M, Loza-Tavera H (2021) Current status on the biodegradability of acrylic polymers: microorganisms, enzymes and metabolic pathways involved. Appl Microbiol Biotechnol 105:991–1006. https://doi.org/10.1007/s00253-020-11073-1

Ge J, Du B, Shen M et al (2023) A review of liquid crystal monomers: environmental occurrence, degradation, toxicity, and human exposure of an emerging class of E-waste pollutants. Environ Pollut 335:122267. https://doi.org/10.1016/j.envpol.2023.122267

Gergoric M, Ekberg C, Steenari B-M (2017) Separation of Heavy Rare-Earth Elements from Light Rare-Earth Elements Via Solvent Extraction from a Neodymium Magnet Leachate and the Effects of Diluents | Journal of Sustainable Metallurgy. J Sustain Metall 3:601–610

Zhurenko EYu, Markusheva TV, Galkin EG (2003) Gluconobacter oxydans IBRB-2T degrades 2,4,5-thrichlorophenoxyacetic acid. Biotechol Russ 75–80. https://doi.org/10.1134/s2079086418020081

Golzar-Ahmadi M, Bahaloo-Horeh N, Pourhossein F et al (2024) Pathway to industrial application of heterotrophic organisms in critical metals recycling from e-waste. Biotechnol Adv 77:108438. https://doi.org/10.1016/j.biotechadv.2024.108438

Golzar-Ahmadi M, Mousavi SM (2021) Extraction of valuable metals from discarded AMOLED displays in smartphones using Bacillus foraminis as an alkali-tolerant strain. Waste Manag 131:226–236. https://doi.org/10.1016/j.wasman.2021.06.006

Gorgieva S, Trček J (2019) Bacterial cellulose: production, modification and perspectives in biomedical applications. Nanomater Basel Switz 9:1352. https://doi.org/10.3390/nano9101352

Graedel TE, Allwood J, Birat J-P et al (2011) What do we know about metal recycling rates? J Ind Ecol 15:355–366. https://doi.org/10.1111/j.1530-9290.2011.00342.x

Grimes SM, Yasri NG, Chaudhary AJ (2017) Recovery of critical metals from dilute leach solutions – separation of indium from tin and lead. Inorganica Chim Acta 461:161–166. https://doi.org/10.1016/j.ica.2017.02.002

Groudeva VI, Krumova K, Groudev SN (2007) Bioleaching of a rich-in-carbonates copper ore at alkaline pH. Adv Mater Res 20:103–106. https://doi.org/10.4028/www.scientific.net/AMR.20-21.103

Gullo M, La China S, Falcone PM, Giudici P (2018) Biotechnological production of cellulose by acetic acid bacteria: current state and perspectives. Appl Microbiol Biotechnol 102:6885–6898. https://doi.org/10.1007/s00253-018-9164-5

Gupta B, Mudhar N, Singh I (2007) Separations and recovery of indium and gallium using bis(2,4,4-trimethylpentyl)phosphinic acid (Cyanex 272). Sep Purif Technol 57:294–303. https://doi.org/10.1016/j.seppur.2007.04.011

Halima NB (2016) Poly(vinyl alcohol): review of its promising applications and insights into biodegradation. RSC Adv 6:39823–39832. https://doi.org/10.1039/C6RA05742J

Han P, Teo WZ, Yew WS (2022) Biologically engineered microbes for bioremediation of electronic waste: wayposts, challenges and future directions. Eng Biol 6:23–34. https://doi.org/10.1049/enb2.12020

Hasegawa H, Rahman IMM, Egawa Y et al (2013) Chelant-induced reclamation of indium from the spent liquid crystal display panels with the aid of microwave irradiation. J Hazard Mater 254:10–17. https://doi.org/10.1016/j.jhazmat.2013.03.028

He S, He J, Wu F et al (2024a) In vivo and in silico toxicity assessment of four common liquid crystal monomers to *Daphnia magna*: novel endocrine disrupting chemicals in crustaceans? Sci Total Environ 912:168757. https://doi.org/10.1016/j.scitotenv.2023.168757

He W, Cui Y, Yang H et al (2024b) Aquatic toxicity, ecological effects, human exposure pathways and health risk assessment of liquid crystal monomers. J Hazard Mater 461:132681. https://doi.org/10.1016/j.jhazmat.2023.132681

Hocker S, Rhudy AK, Ginsburg G, Kranbuehl DE (2014) Polyamide hydrolysis accelerated by small weak organic acids. Polymer 55:5057–5064. https://doi.org/10.1016/j.polymer.2014.08.010

Honarmand M, Golmohammadi M, Naeimi A (2019) Biosynthesis of tin oxide (SnO2) nanoparticles using jujube fruit for photocatalytic degradation of organic dyes. Adv Powder Technol 30:1551–1557. https://doi.org/10.1016/j.apt.2019.04.033

Hoogboom J, Rasing T, Rowan AE, Nolte RJM (2006) LCD alignment layers. Controlling nematic domain properties. J Mater Chem 16:1305–1314. https://doi.org/10.1039/B510579J

Hopfe S, Flemming K, Lehmann F et al (2017) Leaching of rare earth elements from fluorescent powder using the tea fungus Kombucha. Waste Manag 62:211–221. https://doi.org/10.1016/j.wasman.2017.02.005

Hopfe S, Konsulke S, Barthen R et al (2018) Screening and selection of technologically applicable microorganisms for recovery of rare earth elements from fluorescent powder. Waste Manag 79:554–563. https://doi.org/10.1016/j.wasman.2018.08.030

Horta Arduin R, Mathieux F, Huisman J et al (2020) Novel indicators to better monitor the collection and recovery of (critical) raw materials in WEEE: focus on screens. Resour Conserv Recycl 157:104772. https://doi.org/10.1016/j.resconrec.2020.104772

Hou T-C, Jeng S-C (2020) Application of *Bombyx mori* silk fibroin films for liquid-crystal devices. ACS Appl Bio Mater 3:8575–8580. https://doi.org/10.1021/acsabm.0c00959

Houssaine Moutiy E, Tran L-H, Mueller KK et al (2020) Optimized indium solubilization from LCD panels using H_2SO_4 leaching. Waste Manag 114:53–61. https://doi.org/10.1016/j.wasman.2020.07.002

Hu D, Ma B, Li X, Lv Y (2021) Efficient separation and recovery of gallium and indium in spent CIGS materials | Request PDF. Sep Purif Technol. https://doi.org/10.1016/j.seppur.2021.120087

Husemann VE, Werner R (1963) Cellulosesynthese durch Acetobacter xylinum. I. Über Molekulargewicht und Molekulargewichtsverteilung von Bakteriencellulose in Abhängigkeit von der Synthesedauer. Makromol Chem 59:43–60. https://doi.org/10.1002/macp.1963.020590104

Hussain Z, Sajjad W, Khan T, Wahid F (2019) Production of bacterial cellulose from industrial wastes: a review. Cellulose 26:2895–2911. https://doi.org/10.1007/s10570-019-02307-1

Illés IB, Nagy S, Kékesi T (2022) The recycling of pure metallic indium from waste LCD screens by a combined hydro-electrometallurgical method. Hydrometallurgy 213:105945. https://doi.org/10.1016/j.hydromet.2022.105945

Tolcin AC (2017) Indium—2015 minerals yearbook

Işıldar A, van de Vossenberg J, Rene ER et al (2017) Biorecovery of metals from electronic waste. In: Rene ER, Sahinkaya E, Lewis A, Lens PNL (eds) Sustainable heavy metal remediation, vol 2. Case studies. Springer International Publishing, Cham, pp 241–278

Islam MU, Ullah MW, Khan S et al (2017) Strategies for cost-effective and enhanced production of bacterial cellulose. Int J Biol Macromol 102:1166–1173. https://doi.org/10.1016/j.ijbiomac.2017.04.110

Ito F, Amano Y, Nozaki K et al (2004) Hydrolysis of water-soluble and water-insoluble cellulosic substrates by endo-β-1,4-glucanase from Acetobacter xylinum. J Appl Glycosci 51:297–301. https://doi.org/10.5458/jag.51.297

Jadhav U, Su C, Chakankar M, Hocheng H (2017) Acetic acid mediated leaching of metals from lead-free solders. Bioresour Bioprocess 4:42. https://doi.org/10.1186/s40643-017-0173-5

Jafeesh J, Aswathy Aromal S, Krishnan RR (2023) Bio synthesis and characterization of tin oxide for photocatalytic, anti-microbial and anti-oxidant applications. Mater Chem Phys 307:128027. https://doi.org/10.1016/j.matchemphys.2023.128027

Jeon J, Jeon D, Yoo H (2022) Recent Advances in Metal-Oxide Thin-Film Transistors: Flexible/Stretchable Devices, Integrated Circuits, Biosensors, and Neuromorphic Applications. Coatings 12:. https://doi.org/10.3390/coatings12020204

Johnson DB (2018) The evolution, current status, and future prospects of using biotechnologies in the mineral extraction and metal recovery sectors. Minerals 8:343. https://doi.org/10.3390/min8080343

Joshi SJ, Abed RMM (2017) Biodegradation of polyacrylamide and its derivatives. Environ Process 4:463–476. https://doi.org/10.1007/s40710-017-0224-0

Jowkar MJ, Bahaloo-Horeh N, Mousavi SM, Pourhossein F (2018) Bioleaching of indium from discarded liquid crystal displays. J Clean Prod 180:417–429. https://doi.org/10.1016/j.jclepro.2018.01.136

Juchneski NCF, Scherer J, Grochau IH, Veit HM (2013) Disassembly and characterization of liquid crystal screens. Waste Manag Res J Int Solid Wastes Public Clean Assoc ISWA 31:549–558. https://doi.org/10.1177/0734242X13485795

Kadukova J (2016) Surface sorption and nanoparticle production as a silver detoxification mechanism of the freshwater alga *Parachlorella kessleri*. Bioresour Technol 216:406–413. https://doi.org/10.1016/j.biortech.2016.05.104

Kaduková J, Vircíková E (2005) Comparison of differences between copper bioaccumulation and biosorption. Environ Int 31:227–232. https://doi.org/10.1016/j.envint.2004.09.020

Kang HN, Lee J-Y, Kim J-Y (2011) Recovery of indium from etching waste by solvent extraction and electrolytic refining. Hydrometallurgy 110:120–127. https://doi.org/10.1016/j.hydromet.2011.09.009

Kang H, Hong J, Kang D (2014) Liquid crystal alignment behaviors of polystyrene derivatives containing coumarin moieties. Mol Cryst Liq Cryst 605:103–116. https://doi.org/10.1080/15421406.2014.904997

Kang SW, Baek D-H, Ju B-K, Park YW (2021) Green phosphorescent organic light-emitting diode exhibiting highest external quantum efficiency with ultra-thin undoped emission layer. Sci Rep 11:8436. https://doi.org/10.1038/s41598-021-86333-9

Kawai F, Hu X (2009) Biochemistry of microbial polyvinyl alcohol degradation. Appl Microbiol Biotechnol 84:227–237. https://doi.org/10.1007/s00253-009-2113-6

Khezerloo S, Nasirpour N, Pourhossein F, Mousavi SM (2023) Bioleaching of indium from spent light-emitting diode monitors and selective recovery followed by solvent extraction. J Environ Manage 335:117520. https://doi.org/10.1016/j.jenvman.2023.117520

Kim G (2005) A PMMA composite as an optical diffuser in a liquid crystal display backlighting unit (BLU). Eur Polym J 41:1729–1737. https://doi.org/10.1016/j.eurpolymj.2005.02.029

Kim J, Kim E-R, Ihm D (2003) Anisotropic conductive film (ACF) prepared from epoxy/rubber resins and its fabrication and reliability for LCD. J Inf Displ 4:17–23. https://doi.org/10.1080/15980316.2003.9651908

Kim J-W, Choi J, Hong S-J et al (2010) Effects of the concentration of indium-tin-oxide (ITO) ink on the characteristics of directly-printed ITO thin films. J Korean Phys Soc 57:1794–1798. https://doi.org/10.3938/jkps.57.1794

Kirsch P, Bremer M (2000) Nematic liquid crystals for active matrix displays: molecular design and synthesis. Angew Chem Int Ed 39:4216–4235

Kiskira K, Lymperopoulou T, Tsakanika L-A et al (2021) Study of microbial cultures for the bioleaching of scandium from alumina industry by-products. Metals 11:951. https://doi.org/10.3390/met11060951

Krueger MC, Harms H, Schlosser D (2015) Prospects for microbiological solutions to environmental pollution with plastics. Appl Microbiol Biotechnol 99:8857–8874. https://doi.org/10.1007/s00253-015-6879-4

Kulkarni SC, Salunke VT, Naeem S et al (2024) Sustainable synthesis of indium oxide nanoparticles via Aloe Vera for gas sensing applications. Microchem J 207:111941. https://doi.org/10.1016/j.microc.2024.111941

Kumar P, Agrawal N, Pandey V et al (2021) Highly-efficient OLED with cesium fluoride electron injection layer. Solid State Electron 183:108031. https://doi.org/10.1016/j.sse.2021.108031

Kumar Sen S, Raut S (2015) Microbial degradation of low density polyethylene (LDPE): a review. J Environ Chem Eng 3:462–473. https://doi.org/10.1016/j.jece.2015.01.003

Kundu S, Kumar A, Sen S, Nilabh A (2020) Bio-synthesis of SnO2 and comparison its CO sensing performance with conventional processes. J Alloys Compd 818:152841. https://doi.org/10.1016/j.jallcom.2019.152841

Lachka M, Soltisova K, Nosalova L et al (2023) Metal-containing landfills as a source of antibiotic tolerance. Environ Monit Assess 195:262. https://doi.org/10.1007/s10661-022-10873-4

Lahtela V, Virolainen S, Uwaoma A et al (2019) Novel mechanical pre-treatment methods for effective indium recovery from end-of life liquid-crystal display panels. J Clean Prod 230:580–591. https://doi.org/10.1016/j.jclepro.2019.05.163

Lahti J, Vazquez S, Virolainen S et al (2020) Membrane filtration enhanced hydrometallurgical recovery process of indium from waste LCD panels. J Sustain Metall 6:576–588. https://doi.org/10.1007/s40831-020-00293-4

Laricchia F (2025) OLED panel production capacity worldwide 2012–2022. In: Statista. https://www.statista.com/statistics/780342/global-oled-panel-production-capacity-by-technology/. Accessed 7 Oct 2025

Lee S-J, Noon M, Cooper Smith J (2011) Toward the estimation of liquid crystal display materials for waste management and other assessments | IEEE Journals & Magazine | IEEE Xplore. IEEE Trans Compon Packag Manuf Technol. https://doi.org/10.1109/TCPMT.2011.2118760

Lee C-H, Jeong M-K, Fatih Kilicaslan M et al (2013) Recovery of indium from used LCD panel by a time efficient and environmentally sound method assisted HEBM. Waste Manag 33:730–734. https://doi.org/10.1016/j.wasman.2012.10.002

Lee DW, Liu Y, Kim DH et al (2022) Orientation-induced properties of anisotropic polyacrylamide thin layer via plasma treatment in liquid crystal system. Eur Polym J 163:110937. https://doi.org/10.1016/j.eurpolymj.2021.110937

Lee S-J, Cooper J (2008) Estimating regional material flows for LCDs Proceedings of the IEEE international symposium on electronics and the environment ISEE (May 2008). In: 2008 IEEE international symposium on electronics and the environment. IEEE, pp 1–6

Lethukuthula N, Khan MD, Masikane SC et al (2023) Green synthesis of non-stoichiometric indium sulfide (In2.77S4) nanoparticles for water splitting and supercapacitance. Mater Sci Semicond Process 156:107252. https://doi.org/10.1016/j.mssp.2022.107252

Li J, Gao S, Duan H, Liu L (2009) Recovery of valuable materials from waste liquid crystal display panel. Waste Manag 29:2033–2039. https://doi.org/10.1016/j.wasman.2008.12.013

Li Y, Liu Z, Li Q et al (2011) Recovery of indium from used indium–tin oxide (ITO) targets. Hydrometallurgy 105:207–212. https://doi.org/10.1016/j.hydromet.2010.09.006

Li J, Su G, Letcher RJ et al (2018) Liquid crystal monomers (LCMs): a new generation of persistent bioaccumulative and toxic (PBT) compounds? Environ Sci Technol 52:5005–5006. https://doi.org/10.1021/acs.est.8b01636

Li Y, Zhu N, Wei X et al (2020) Leaching of indium from waste LCD screens by oxalic acid in temperature-controlled aciduric stirred reactor. Process Saf Environ Prot 133:137–148. https://doi.org/10.1016/j.psep.2019.10.026

Li J, Yin Y, Meng H (2024) Research progress of color photoresists for TFT-LCD. Dyes Pigments 225:112094. https://doi.org/10.1016/j.dyepig.2024.112094

Li X, Li P, Lu Y et al (2025) Liquid crystal monomers as emerging contaminants: contaminated distribution, environmental behavior, detection technologies, and future challenges. Environ Health 3:1125–1138. https://doi.org/10.1021/envhealth.5c00071

Liang X, Xie R, Zhu C et al (2021) Comprehensive identification of liquid crystal monomers-biphenyls, cyanobiphenyls, fluorinated biphenyls, and their analogues-in waste LCD panels and the first estimate of their global release into the environment. Environ Sci Technol 55:12424–12436. https://doi.org/10.1021/acs.est.1c03901

Lme (2025). https://www.lme.com/

Liu B-W, Zhao H-B, Wang Y-Z (2022) Advanced flame-retardant methods for polymeric materials. Adv Mater 34:2107905. https://doi.org/10.1002/adma.202107905

López-Yáñez A, Alonso A, Vengoechea-Pimienta A, Ramírez-Muñoz J (2019) Indium and tin recovery from waste LCD panels using citrate as a complexing agent. Waste Manag 96:181–189. https://doi.org/10.1016/j.wasman.2019.07.030

Lumio RT, Tan MA, Magpantay HD (2021) Biotechnology-based microbial degradation of plastic additives. 3 Biotech 11:350. https://doi.org/10.1007/s13205-021-02884-8

Luo D, Zhu N, Li Y et al (2019) Simultaneous leaching and extraction of indium from waste LCDs with acidic ionic liquids. Hydrometallurgy 189:105146. https://doi.org/10.1016/j.hydromet.2019.105146

Mamlouk D, Gullo M (2013) Acetic acid bacteria: physiology and carbon sources oxidation. Indian J Microbiol 53:377–384. https://doi.org/10.1007/s12088-013-0414-z

Mandal G, Bauri J, Choudhary RB (2024) Conjugated polymeric nanocomposite-based light-generating active materials for OLED applications: a review. Mater Sci Eng B Solid-State Mater Adv Technol 303:117271. https://doi.org/10.1016/j.mseb.2024.117271

Martelo LM, Silva MAD, Bacelo HAM et al (2025) Physical—chemical hybrid process for separating all raw materials from the waste of liquid crystal displays screens of smartphones. J Hazard Mater Adv 18:100735. https://doi.org/10.1016/j.hazadv.2025.100735

Maeda K, Ueda S, Inoue R (2022) Extraction of Rare Earth Metal Oxide Inclusion Particles in Steel. ISIJ Int 62:904–911. https://doi.org/10.2355/isijinternational.ISIJINT-2021-424

Mensah RA, Shanmugam V, Narayanan S et al (2022) A review of sustainable and environment-friendly flame retardants used in plastics. Polym Test 108:107511. https://doi.org/10.1016/j.polymertesting.2022.107511

Merugu R, Gothalwal R (2021) Green synthesis and characterisation of Indium Tin oxide nanoparticles using toddy palm from *Borassus flabellifer*. Mater Today Proc 47:4167–4170. https://doi.org/10.1016/j.matpr.2021.04.447

Mishra S, Ghosh S, van Hullebusch ED et al (2023) A critical review on the recovery of base and critical elements from electronic waste-contaminated streams using microbial biotechnology. Appl Biochem Biotechnol 195:7859–7888. https://doi.org/10.1007/s12010-023-04440-x

Mori N, Morimoto M, Nakamura K (1999) Cellulose films as alignment layers for liquid crystals: application of flow-induced molecular orientation. Adv Mater 11:1049–1051

Nakano Y, Biegasiewicz KF, Hyster TK (2019) Biocatalytic hydrogen atom transfer: an invigorating approach to free-radical reactions. Curr Opin Chem Biol 49:16–24. https://doi.org/10.1016/j.cbpa.2018.09.001

Naomi R, Bt Hj Idrus R, Fauzi MB (2020) Plant- vs. bacterial-derived cellulose for wound healing: a review. Int J Environ Res Public Health 17:6803. https://doi.org/10.3390/ijerph17186803

Narancic T, O'Connor KE (2019) Plastic waste as a global challenge: are biodegradable plastics the answer to the plastic waste problem? Microbiol Read Engl 165:129–137. https://doi.org/10.1099/mic.0.000749

Nyyssölä A, Ahlgren J (2019) Microbial degradation of polyacrylamide and the deamination product polyacrylate. Int Biodeterior Biodegrad 139:24–33. https://doi.org/10.1016/j.ibiod.2019.02.005

Ober JA (2017) Mineral commodity summaries 2017. U.S. Geological Survey

Olivato JB, Grossmann MVE, Bilck AP, Yamashita F (2012) Effect of organic acids as additives on the performance of thermoplastic starch/polyester blown films. Carbohydr Polym 90:159–164. https://doi.org/10.1016/j.carbpol.2012.05.009

Pant D (2014) A review of electronic waste management microbial participation: a green technology | Request PDF. Int J Environ Waste Manag 13:23–36. https://doi.org/10.1504/IJEWM.2014.058791

Parsa A, Bahaloo Horeh N, Mousavi SM (2024) A hybrid thermal-biological recycling route for efficient extraction of metals and metalloids from end-of-life liquid crystal displays (LCDs). Chemosphere 352:141408. https://doi.org/10.1016/j.chemosphere.2024.141408

Patel A, Patel P, Shukla A et al (2023) Sustainable bioconversion of industrial wastes into bacterial cellulose for diverse applications: a way towards pollution control and abatement. Curr Pollut Rep 9:226–242. https://doi.org/10.1007/s40726-023-00257-8

Peeters JR, Vanegas P, Tange L et al (2014) Closed loop recycling of plastics containing Flame Retardants. Resour Conserv Recycl 84:35–43. https://doi.org/10.1016/j.resconrec.2013.12.006
Peeters JR, Vanegas P, Kellens K et al (2015) Forecasting waste compositions: a case study on plastic waste of electronic display housings. Waste Manag 46:28–39. https://doi.org/10.1016/j.wasman.2015.09.019
Peng L (2003) Study on UV-curable adhesives and its application in LCD assembly. Adhes China
Pereira EB, Suliman AL, Tanabe EH, Bertuol DA (2018) Recovery of indium from liquid crystal displays of discarded mobile phones using solvent extraction. Miner Eng 119:67–72. https://doi.org/10.1016/j.mineng.2018.01.022
Pieper DH, Seeger M (2008) Bacterial metabolism of polychlorinated biphenyls. J Mol Microbiol Biotechnol 15:121–138. https://doi.org/10.1159/000121325
Polman EMN, Gruter G-JM, Parsons JR, Tietema A (2021) Comparison of the aerobic biodegradation of biopolymers and the corresponding bioplastics: a review. Sci Total Environ 753:141953. https://doi.org/10.1016/j.scitotenv.2020.141953
Pooja N, Chakraborty I, Rahman MH, Mazumder N (2023) An insight on sources and biodegradation of bioplastics: a review. 3 Biotech 13:220. https://doi.org/10.1007/s13205-023-03638-4
Pourhossein F, Mousavi SM (2019) A novel step-wise indirect bioleaching using biogenic ferric agent for enhancement recovery of valuable metals from waste light emitting diode (WLED). J Hazard Mater 378:120648. https://doi.org/10.1016/j.jhazmat.2019.05.041
Pourhossein F, Mousavi SM, Beolchini F, Lo Martire M (2021) Novel green hybrid acidic-cyanide bioleaching applied for high recovery of precious and critical metals from spent light emitting diode lamps. J Clean Prod 298:126714. https://doi.org/10.1016/j.jclepro.2021.126714
Pourhossein F, Mousavi SM, Beolchini F (2022) Innovative bio-acid leaching method for high recovery of critical metals from end-of-life light emitting diodes. Resour Conserv Recycl 182:106306. https://doi.org/10.1016/j.resconrec.2022.106306
Profumo A, Sturini M, Maraschi F et al (2008) Selective sequential dissolution for the determination of inorganic indium compounds in the particulate matter of emissions and workplace air. Anal Sci 24:427–430. https://doi.org/10.2116/analsci.24.427
Qin J, Ning S, Fujita T et al (2021) Leaching of indium and tin from waste LCD by a time-efficient method assisted planetary high energy ball milling. Waste Manag 120:193–201. https://doi.org/10.1016/j.wasman.2020.11.028
Qin J, Ning S, Zeng J et al (2023) Leaching behavior and process optimization of tin recovery from waste liquid crystal display under mechanical activation. J Clean Prod 399:136640. https://doi.org/10.1016/j.jclepro.2023.136640
OLEDWorks (2025) https://www.oledworks.com/oled-lighting-products/sustainability/
QUMEC (2020) Rare metals have huge potential for recycling in Europe | Research and Innovation. https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/rare-metals-have-huge-potential-recycling-europe. Accessed 30 June 2025
Qu Y, Li H, Wang X, et al (2019) Bioleaching of Major, Rare Earth, and Radioactive Elements from Red Mud by using Indigenous Chemoheterotrophic Bacterium Acetobacter sp. Minerals 9. https://doi.org/10.3390/min9020067
Raspor P, Goranovic D (2008) Biotechnological applications of acetic acid bacteria. Crit Rev Biotechnol 28:101–124. https://doi.org/10.1080/07388550802046749
Raza H, Athar M, Faroo U et al (2014) Chemically modified biomass from *Triticum aestivum* for eco-friendly detoxification of Cd(II)- and Sn(II)-contaminated waters. Pol J Environ Stud 23:2163–2174
Buchert M, Manhart A, Bleher D, Pingel D (2012) Recycling critical raw materials from waste electronic equipment
Rendón-Castrillón L, Ramírez-Carmona M, Ocampo-López C, Gómez-Arroyave L (2023) Bioleaching techniques for sustainable recovery of metals from solid matrices. Sustainability 15:10222. https://doi.org/10.3390/su151310222
Restrepo-Flórez J-M, Bassi A, Thompson MR (2014) Microbial degradation and deterioration of polyethylene – a review. Int Biodeterior Biodegrad 88:83–90. https://doi.org/10.1016/j.ibiod.2013.12.014
Rezaei O, Mousavi SM, Pourhossein F (2018) Recovery of Indium from mobile phone touch screen using adapted Acidithiobacillus ferrooxidans. Int J Biosci Biochem Bioinform 8:117–124. https://doi.org/10.17706/ijbbb.2018.8.2.117-124
Ritcey GM (1980) Crud in solvent extraction processing — a review of causes and treatment. Hydrometallurgy 5:97–107. https://doi.org/10.1016/0304-386X(80)90031-6
Rocchetti L, Amato A, Fonti V et al (2015) Cross-current leaching of indium from end-of-life LCD panels. Waste Manag 42:180–187. https://doi.org/10.1016/j.wasman.2015.04.035
Rocchetti L, Amato A, Beolchini F (2016) Recovery of indium from liquid crystal displays. J Clean Prod 116:299–305. https://doi.org/10.1016/j.jclepro.2015.12.080
Rocchetti L, Amato A, Beolchini F (2016) Recovery of indium from liquid crystal displays. J Clean Prod 116:299–305. https://doi.org/10.1016/j.jclepro.2015.12.080
Romagnoli V, Bruijne E de, Drapeau P et al (2022) Study on options for return schemes of mobile phones, tablets and other small electrical and electronic equipment in the EU. Publications Office of the European Union
Rozina AM, Ahmad M et al (2023) Transformation of waste seed biomass of *Cordia myxa* into valuable bioenergy through membrane bioreactor using green nanoparticles of indium oxide. Chemosphere 314:137604. https://doi.org/10.1016/j.chemosphere.2022.137604
Ru J, Huo Y, Yang Y (2020) Microbial degradation and valorization of plastic wastes. Front Microbiol. https://doi.org/10.3389/fmicb.2020.00442
Ruan J, Guo Y, Qiao Q (2012) Recovery of indium from scrap TFT-LCDs by solvent extraction. Procedia Environ Sci 16:545–551. https://doi.org/10.1016/j.proenv.2012.10.075

Ruiz-Mercado GJ, Gonzalez MA, Smith RL, Meyer DE (2017) A conceptual chemical process for the recycling of Ce, Eu, and Y from LED flat panel displays. Resour Conserv Recycl 126:42–49. https://doi.org/10.1016/j.resconrec.2017.07.009

Rusinova-Videva S, Nachkova S, Adamov A, Dimitrova-Dyulgerova I (2020) Antarctic yeast *Cryptococcus laurentii* (AL65): biomass and exopolysaccharide production and biosorption of metals. J Chem Technol Biotechnol 95:1372–1379. https://doi.org/10.1002/jctb.6321

Saichana N, Matsushita K, Adachi O et al (2015) Acetic acid bacteria: A group of bacteria with versatile biotechnological applications. Biotechnol Adv 33:1260–1271. https://doi.org/10.1016/j.biotechadv.2014.12.001

Samsung (2025) Home—Samsung Business Insights. https://insights.samsung.com/

Sato T, Sato K (1992) Liquid-liquid extraction of indium (III) from aqueous acid solutions by acid organophosphorus compounds. Hydrometallurgy 30:367–383. https://doi.org/10.1016/0304-386X(92)90094-G

Savvilotidou V, Hahladakis JN, Gidarakos E (2014) Determination of toxic metals in discarded Liquid Crystal Displays (LCDs). Resour Conserv Recycl 92:108–115. https://doi.org/10.1016/j.resconrec.2014.09.002

Savvilotidou V, Hahladakis JN, Gidarakos E (2015) Leaching capacity of metals–metalloids and recovery of valuable materials from waste LCDs. Waste Manag 45:314–324. https://doi.org/10.1016/j.wasman.2015.05.025

Savvilotidou V, Kousaiti A, Batinic B et al (2019) Evaluation and comparison of pre-treatment techniques for recovering indium from discarded liquid crystal displays. Waste Manag 87:51–61. https://doi.org/10.1016/j.wasman.2019.01.029

Schueler TA, Schippers A, Goldmann D (2024) Bioleaching for metals removal from mine tailings flotation fractions. Hydrometallurgy 225:106286. https://doi.org/10.1016/j.hydromet.2024.106286

Schuster J, Ebin B (2021) Investigation of indium and other valuable metals leaching from unground waste LCD screens by organic and inorganic acid leaching. Sep Purif Technol 279:119659. https://doi.org/10.1016/j.seppur.2021.119659

Sedlakova-Kadukova J (2022) Chapter 4 - Microorganisms in metal recovery—tools or teachers? In: Pratap Singh R, Manchanda G, Bhattacharjee K, Panosyan H (eds) Microbial syntrophy-mediated eco-enterprising. Academic Press, pp 71–86

Sedlakova-Kadukova J, Sincak M, Demčakova V (2025) Does the silver nanoparticles production route affect the proliferation of antibiotic resistance in soil ecosystem? Antibiotics 14:15. https://doi.org/10.3390/antibiotics14010015

Shah AA, Kato S, Shintani N et al (2014) Microbial degradation of aliphatic and aliphatic-aromatic co-polyesters. Appl Microbiol Biotechnol 98:3437–3447. https://doi.org/10.1007/s00253-014-5558-1

shanti sree B, Yaramma Reddy A, Srinivasa Rao B, latha Chittur K (2019) Green fabrication and characterization of In2O3-Sno2 nanocomposite from acacia gum. Mater Today: Proceed 18:5351–5355. https://doi.org/10.1016/j.matpr.2019.07.561

Shanti Sree B, Aparna Y, Anil Babu T et al (2021) Indium tin oxide nanocomposites—green synthesis, characterization, morphology and optical properties using almond gum. Lett Appl NanoBioScience 11:3134–3141. https://doi.org/10.33263/LIANBS111.31343141

Shen Y, Yuan R, Chen X et al (2018) Co-pyrolysis of E-waste nonmetallic residues with biowastes. ACS Sustain Chem Eng 6:9086–9093. https://doi.org/10.1021/acssuschemeng.8b01439

Shin D, Kim J, Kim B-s et al (2015) Use of phosphate solubilizing bacteria to leach rare earth elements from Monazite-bearing ore. Minerals 5:189–202. https://doi.org/10.3390/min5020189

Sherif A (2025) IHS Markit's annual revenue 2012–2021. In: Statista. https://www.statista.com/statistics/798181/worldwide-ihs-markit-annual-revenue/?srsltid=AfmBOorbXBXPJK91TgZ0S-rWN4FLDi1coN6XHw7q3dxZjUve7HBPj3AG. Accessed 7 Oct 2025

Siddique M, Subhan W, Naz F, Nawaz A (2022) Biosynthesis of highly porous Ag/Bi/SnO2 nanohybrid material using seeds extract of *Caesalpinia bonduc* and their photocatalytic activity. Phys B Condens Matter 644:414209. https://doi.org/10.1016/j.physb.2022.414209

Silveira AVM, Fuchs MS, Pinheiro DK et al (2015) Recovery of indium from LCD screens of discarded cell phones. Waste Manag 45:334–342. https://doi.org/10.1016/j.wasman.2015.04.007

Singh BK, Walker A (2006) Microbial degradation of organophosphorus compounds. FEMS Microbiol Rev 30:428–471. https://doi.org/10.1111/j.1574-6976.2006.00018.x

Song J (2022) Organic light emitting diode and liquid crystal display: structure, mechanism, preparation, and comparison. Highlights Sci Eng Technol 21:7–13. https://doi.org/10.54097/hset.v21i.3132

Souada M, Louage C, Doisy J-Y et al (2018) Extraction of indium-tin oxide from end-of-life LCD panels using ultrasound assisted acid leaching. Ultrason Sonochem 40:929–936. https://doi.org/10.1016/j.ultsonch.2017.08.043

Stępień M, Palimąka P, Bukowska A (2017) Impact of selected parameters on extraction of indium from LCD screens. Metall Foundry Eng 43:305–305. https://doi.org/10.7494/mafe.2017.43.4.305

Su J-Y, Syu C-H, Lee D-Y (2018) Growth inhibition of rice (*Oryza sativa* L.) seedlings in Ga- and In-contaminated acidic soils is respectively caused by Al and Al+In toxicity. J Hazard Mater 344:274–282. https://doi.org/10.1016/j.jhazmat.2017.10.023

Su H, Ren K, Li R et al (2022) Suspect screening of liquid crystal monomers (LCMs) in sediment using an established database covering 1173 LCMs. Environ Sci Technol 56:8061–8070. https://doi.org/10.1021/acs.est.2c01130

Sugiura T (1993) Dyed color filters for liquid-crystal displays. J Soc Inf Disp 1:177–180. https://doi.org/10.1889/1.1984856

Sun Z, Cao H, Xiao Y et al (2017) Toward sustainability for recovery of critical metals from electronic waste: the hydrochemistry processes. ACS Sustain Chem Eng 5:21–40. https://doi.org/10.1021/acssuschemeng.6b00841

Suzuki R, Nagura M, Sasada Y et al (2015) 31.1: Evolution of cellulose triacetate (TAC) films for LCDs: novel technologies for high hardness, durability, and dimensional stability. SID Symp Digest Tech Papers 46:446–449. https://doi.org/10.1002/sdtp.10413

Swain B, Mishra C, Hong HS, Cho S-S (2016) Beneficiation and recovery of indium from liquid-crystal-display glass by hydrometallurgy. Waste Manag 57:207–214. https://doi.org/10.1016/j.wasman.2016.02.019

Swain AA, Oraon R, Bauddh K, Kumar M (2022) Biowaste valorization for production of bacterial cellulose and its multifarious applications contributing to environmental sustainability. Environ Sustain 5:51–63. https://doi.org/10.1007/s42398-022-00221-0

Tang Y, Zhu G, Li Y et al (2023) Failure analysis of polarizer of liquid crystal display. J Fail Anal Prev 23:2673–2682. https://doi.org/10.1007/s11668-023-01800-x

Talens PL, Nuss P, Mathieux F, Blengini G (2018) Towards recycling indicators based on EU flows and raw materials system analysis data. In: JRC Publ. Repos. https://publications.jrc.ec.europa.eu/repository/handle/JRC112720. Accessed 30 June 2025

Tao X, Wu R, Xia Y et al (2014) Biotemplated fabrication of Sn@C anode materials based on the unique metal biosorption behavior of microalgae. ACS Appl Mater Interfaces 6:3696–3702. https://doi.org/10.1021/am500020e

Tao D, Jin Q, Ruan Y et al (2022) Widespread occurrence of emerging E-waste contaminants—liquid crystal monomers in sediments of the Pearl River Estuary, China. J Hazard Mater 437:129377. https://doi.org/10.1016/j.jhazmat.2022.129377

Tarumi K, Bremer M, Geelhaar T (1997) Recent liquid crystal material development for active matrix displays. Annu Rev Mater Res 27:423–441. https://doi.org/10.1146/annurev.matsci.27.1.423

Trading economics (2025). https://pl.tradingeconomics.com/commodities. Accessed 6 Oct 2025

Toache-Pérez AD, Bolarín-Miró AM, Sánchez-De Jesús F, Lapidus GT (2020) Facile method for the selective recovery of Gd and Pr from LCD screen wastes using ultrasound-assisted leaching. Sustain Environ Res 30:20. https://doi.org/10.1186/s42834-020-00060-w

Toache-Pérez AD, Lapidus GT, Bolarín-Miró AM, De Jesús FS (2022) Selective leaching and recovery of Er, Gd, Sn, and In from liquid crystal display screen waste by sono-leaching assisted by magnetic separation. ACS Omega 7:31897–31904. https://doi.org/10.1021/acsomega.2c02729

Tonouchi N (2016) Cellulose and other capsular polysaccharides of acetic acid bacteria. Acetic acid bacteria. Springer, Japan, pp 299–320

Tonouchi N, Tahara N, Kojima Y et al (1997) A beta-glucosidase gene downstream of the cellulose synthase operon in cellulose-producing Acetobacter. Biosci Biotechnol Biochem 61:1789–1790. https://doi.org/10.1271/bbb.61.1789

Trček J, Dogsa I, Accetto T, Stopar D (2021) Acetan and Acetan-like polysaccharides: genetics, biosynthesis, structure, and viscoelasticity. Polymers 13:815. https://doi.org/10.3390/polym13050815

Ul-Islam M, Ullah MW, Khan S, Park JK (2020) Production of bacterial cellulose from alternative cheap and waste resources: a step for cost reduction with positive environmental aspects. Korean J Chem Eng 37:925–937. https://doi.org/10.1007/s11814-020-0524-3

Urbanek AK, Mirończuk AM, García-Martín A et al (2020) Biochemical properties and biotechnological applications of microbial enzymes involved in the degradation of polyester-type plastics. Biochimica Et Biophysica Acta (BBA)—Proteins Proteomics 1868:140315. https://doi.org/10.1016/j.bbapap.2019.140315

Velásquez-Riaño M, Bojacá V (2017) Production of bacterial cellulose from alternative low-cost substrates. Cellulose 24:2677–2698. https://doi.org/10.1007/s10570-017-1309-7

Villagrán Z, Anaya-Esparza LM, Velázquez-Carriles CA et al (2024) Plant-based extracts as reducing, capping, and stabilizing agents for the green synthesis of inorganic nanoparticles. Resources 13:70. https://doi.org/10.3390/resources13060070

Virolainen S, Ibana D, Paatero E (2011) Recovery of indium from indium tin oxide by solvent extraction. Hydrometallurgy 107:56–61. https://doi.org/10.1016/j.hydromet.2011.01.005

Waaijers SL, Parsons JR (2016) Biodegradation of brominated and organophosphorus flame retardants. Curr Opin Biotechnol 38:14–23. https://doi.org/10.1016/j.copbio.2015.12.005

Wang H-Y (2009) A study of the effects of LCD glass sand on the properties of concrete. Waste Manag 29:335–341. https://doi.org/10.1016/j.wasman.2008.03.005

Wang R, Xu Z (2016) Pyrolysis characteristics and pyrolysis products separation for recycling organic materials from waste liquid crystal display panels. J Hazard Mater 302:45–56. https://doi.org/10.1016/j.jhazmat.2015.09.038

Wang H-Y, Zeng H, Wu J-Y (2014) A study on the macro and micro properties of concrete with LCD glass. Constr Build Mater 50:664–670. https://doi.org/10.1016/j.conbuildmat.2013.09.015

Wang S, He Y, Zhang T, Zhang G (2017) Recovery of valuable components from waste LCD panel through a dry physical method. Waste Manag 64:255–262. https://doi.org/10.1016/j.wasman.2017.03.038

Wang Y, Wang R, Zhang C, Wang J (2021) Full components recovery of organic matter and indium from discarded liquid crystal display panels. J Clean Prod 299:126862. https://doi.org/10.1016/j.jclepro.2021.126862

Wang F, Bu H, Wang Y et al (2023) Estimation of global waste smartphones and embedded critical raw materials: an industry life cycle perspective. Resour Conserv Recycl 196:107063. https://doi.org/10.1016/j.resconrec.2023.107063

Wang Y, Jin Q, Lin H et al (2024) A review of liquid crystal monomers (LCMs) as emerging contaminants: environmental occurrences, emissions, exposure routes and toxicity. J Hazard Mater 480:135894. https://doi.org/10.1016/j.jhazmat.2024.135894

Wang N, Han H, Zhang Z et al (2025) Impact of sodium carboxymethyl cellulose on redispersibility and polishing performance of lanthanum-cerium-based slurry

containing sodium hexametaphosphate. J Rare Earths 43:851–858. https://doi.org/10.1016/j.jre.2024.06.021
Werner A, Rieger A, Helbig K, Brix B (2019) Nanofiltration for the recovery of indium and germanium from bioleaching solutions | Request PDF. Sep Purif Technol. https://doi.org/10.1016/j.seppur.2019.05.025
Willner J, Fornalczyk A, Gajda B, Saternus M (2018) Bioleaching of indium and tin from used LCD panels. Physicochem Probl Miner Process 54:639–645. https://doi.org/10.5277/ppmp1878
Willner J, Fornalczyk A, Jablonska-Czapla M et al (2021) Studies on the content of selected technology critical elements (Germanium, Tellurium and Thallium) in electronic waste. Materials 14:3722. https://doi.org/10.3390/ma14133722
Willner J, Janakova I, Jablonska-Czapla M et al (2025) Indium recovery from ITO in LCD glass using magnetic separation and sulfuric acid: influence of fractions and process conditions. Processes 13:3917. https://doi.org/10.3390/pr13123917
van Wyk N, Fischer D, Wilbers D et al (2024) Toward the bioleaching of bauxite residue by *Gluconobacter oxydans*. J Appl Microbiol 135:lxae279. https://doi.org/10.1093/jambio/lxae279
Xiao L, Wang L, Zhao T et al (2026) Indium resource industry chain status and supply and demand trend analysis. Miner Eng 235:109780. https://doi.org/10.1016/j.mineng.2025.109780
Xie Y, Wang S, Tian X et al (2019) Leaching of indium from end-of-life LCD panels via catalysis by synergistic microbial communities. Sci Total Environ 655:781–786. https://doi.org/10.1016/j.scitotenv.2018.11.141
Xie J-F, Wei G-L, Zeng L-X, Liu L-Y (2024) Liquid crystal monomers in soils near the e-waste recycling site and liquid crystal display manufacturer: exponential decrease with distance. Sci Total Environ 909:168428. https://doi.org/10.1016/j.scitotenv.2023.168428
Xu L, Chen G, Zhang X et al (2024) Waste ITO target recycling for efficient indium recovery through a closed-loop process. J Environ Chem Eng 12:112136. https://doi.org/10.1016/j.jece.2024.112136
Yaashikaa PR, Priyanka B, Senthil Kumar P et al (2022) A review on recent advancements in recovery of valuable and toxic metals from e-waste using bioleaching approach. Chemosphere 287:132230. https://doi.org/10.1016/j.chemosphere.2021.132230
Yan L, Zhu Q, Ikeda T (2001) Ethyl cellulose films as alignment layers for liquid crystals. J Appl Polym Sci 82:2770–2774. https://doi.org/10.1002/app.2130
Yang J, Retegan T, Steenari B-M, Ekberg C (2016) Recovery of indium and yttrium from flat panel display waste using solvent extraction. Sep Purif Technol 166:117–124. https://doi.org/10.1016/j.seppur.2016.04.021
Yang R, Xu X, Wang X et al (2024) Fluorinated liquid-crystal monomers in serum from the general population and their impact on human health. Environ Sci Technol 58:15949–15959. https://doi.org/10.1021/acs.est.4c02905
Yang J, Retegan T, Ekberg C (2013) Indium recovery from discarded LCD panel glass by solvent extraction. Hydrometallurgy 137:68–77. https://doi.org/10.1016/j.hydromet.2013.05.008
Yao L-L, Wang J-L, Xu R-F et al (2023) Occurrence of liquid crystal monomers in indoor and outdoor air particle matters (PM10): implications for human exposure indoors. Sci Total Environ 905:166964. https://doi.org/10.1016/j.scitotenv.2023.166964
Yen F-C, Chang T-C, Laohaprapanon S, Chen Y-L (2016) Recovery of indium from LCD waste by solvent extraction and the supported liquid membrane with strip dispersion using D2EHPA as the extractant. Solvent Extr Res Dev, Jpn 23:63–73. https://doi.org/10.15261/serdj.23.63
Yoo D-Y, Lee Y, You I et al (2022) Utilization of liquid crystal display (LCD) glass waste in concrete: a review. Cem Concr Compos 130:104542. https://doi.org/10.1016/j.cemconcomp.2022.104542
Yoon S, Teets TS (2021) Red to near-infrared phosphorescent Ir(iii) complexes with electron-rich chelating ligands—chemical communications (RSC Publishing). Chem Commun. https://doi.org/10.1039/D0CC08067E
Yu P, Cao S, Shan Y et al (2022) Highly efficient green InP-based quantum dot light-emitting diodes regulated by inner alloyed shell component. Light Sci Appl 11:162. https://doi.org/10.1038/s41377-022-00855-z
Zeng X, Wang F, Sun X, Li J (2015) Recycling indium from scraped glass of liquid crystal display: process optimizing and mechanism exploring. ACS Sustain Chem Eng 3:1306–1312. https://doi.org/10.1021/acssuschemeng.5b00020
Zhang K, Wu Y, Wang W et al (2015) Recycling indium from waste LCDs: a review. Resour Conserv Recycl 104:276–290. https://doi.org/10.1016/j.resconrec.2015.07.015
Zhang M, Buekens A, Li X (2016) Brominated flame retardants and the formation of dioxins and furans in fires and combustion. J Hazard Mater 304:26–39. https://doi.org/10.1016/j.jhazmat.2015.10.014
Zhang S, Ding Y, Liu B, Chang C (2017) Supply and demand of some critical metals and present status of their recycling in WEEE. Waste Manag 65:113–127. https://doi.org/10.1016/j.wasman.2017.04.003
Zhang W, Lin Y-C, Chien S-K et al (2020) Efficient indium leaching and recovery from waste liquid crystal displays panels using microwave and ultrasound-assisted heating system. Sep Purif Technol 250:117154. https://doi.org/10.1016/j.seppur.2020.117154
Zhang N, Ding M, Yuan Y (2022) Current advances in biodegradation of polyolefins. Microorganisms 10:1537. https://doi.org/10.3390/microorganisms10081537
Zhang K, Zhang T-T, Guo R-R et al (2023) The regulation of key flavor of traditional fermented food by microbial metabolism: a review. Food Chem X 19:100871. https://doi.org/10.1016/j.fochx.2023.100871
Zheng K, Benedetti MF, van Hullebusch ED (2023) Recovery technologies for indium, gallium, and germanium from end-of-life products (electronic waste) – a review. J Environ Manage 347:119043. https://doi.org/10.1016/j.jenvman.2023.119043
Zheng K, Benedetti MF, Jain R et al (2024) Selective leaching of indium from spent LCD screens by siderophore desferrioxamine E. J Hazard Mater 469:134013. https://doi.org/10.1016/j.jhazmat.2024.134013
Zhu M, Shen M, Liang X et al (2021) Identification of environmental liquid-crystal monomers: a class of new persistent organic pollutants—fluorinated biphenyls and analogues—emitted from E-waste dismantling. Environ

Sci Technol 55:5984–5992. https://doi.org/10.1021/acs.est.1c00112

Zhu X, Yu Y, Meng W et al (2024) Aerobic microbial transformation of fluorinated liquid crystal monomer: new pathways and mechanism. Environ Sci Technol 58:510–521. https://doi.org/10.1021/acs.est.3c04256