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TOPICAL REVIEW

Innovation in compound semiconductors and optoelectronics: structural limits and pathways to sustainability and circularity

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Abstract

Compound semiconductors are increasingly used in electronics and optoelectronic technologies, but their manufacturing, processing, and disposal have significant environmental and resource costs. As the worldwide demand for photonics, sensing, and high-performance electronic devices grows, sustainability and circularity have evolved from peripheral issues to structural constraints. This Topical Review covers recent breakthroughs in materials design, semiconductor production, electronic waste recycling, and life-cycle assessment for optoelectronic and compound semiconductor systems. Emerging solutions such as organic and biodegradable electronics, recyclable substrates, and dissolvable packaging are compared to process-level efforts to lower energy, water, and chemical intensity during manufacturing. Crucially, examination of real-world e-waste systems demonstrates that end-of-life recovery of III–V semiconductors remain highly limited under current industrial recycling infrastructures, resulting in substantial dissipation of critical elements across waste streams. The issues addressed in this review align directly with UN Sustainable Development Goals SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), with proposed strategies intended to advance circularity and resource efficiency without compromising broader development objectives. These findings indicate that meaningful circularity must be achieved primarily through upstream material selection, process redesign, and life-cycle-informed system strategies, rather than relying on downstream recycling alone.

1. Introduction

Electronics and optoelectronics have become one of the fastest-growing and most resource-intensive manufacturing domains globally, underpinned by semiconductor devices, vertical-cavity surface-emitting laser, photodetectors, light-emitting diodes (LEDs), displays, and artificial intelligence-accelerated computing hardware. Their fabrication demands high electricity input, extensive ultrapure-water usage, and large volumes of specialty gases and chemicals, resulting in significant greenhouse-gas emissions and hazardous waste streams [1, 2]. In addition, many of the materials enabling advanced optoelectronic performance such as gallium, indium, and germanium are technology-critical elements with geographically concentrated and geopolitically fragile supply chains, meaning that risks in extraction, refining, and trade disruptions can propagate directly into semiconductor production [3].

Although these devices contain valuable elements, they ultimately contribute to one of the world's fastest-growing solid-waste streams. Global electronic-waste (e-waste) generation surpassed 62 Mt in 2022, yet the recovery of critical elements remains extremely low Ga <1%, In <1%, and even Au rarely exceeds 20%–30% [4, 5]. Most of this waste consists of silicon-based electronics. While silicon wafer reclaim is well established in manufacturing environments, silicon becomes effectively non-recoverable

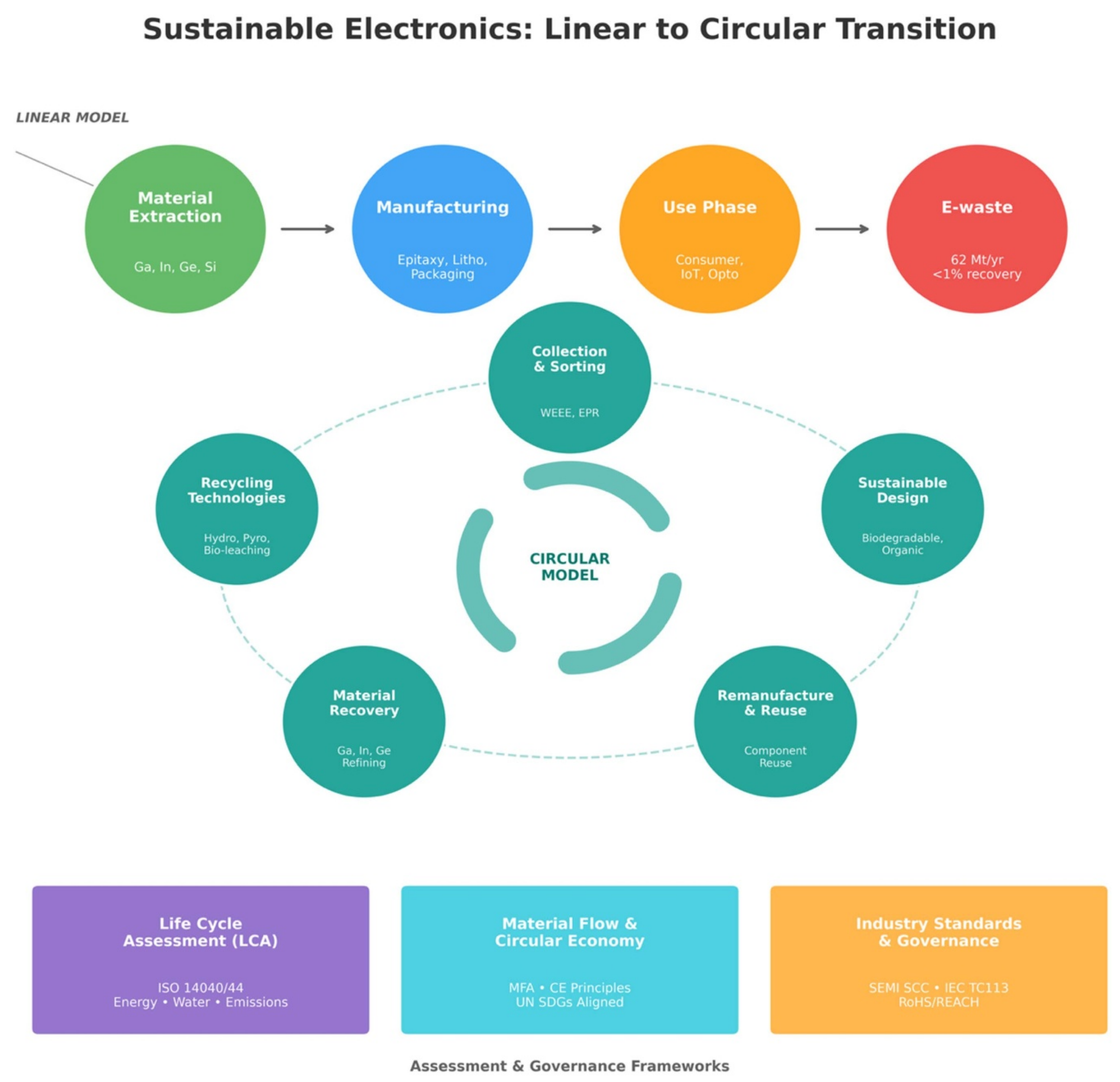

Figure 1. Schematic comparison of linear and circular models in electronics and optoelectronics, highlighting material extraction, manufacturing, use, and end-of-life pathways. Colors and directional arrows distinguish the transition from a conventional linear electronics model to a circular framework incorporating material recovery, recycling, and sustainable design strategies.

once embedded in complex multi-material packaging and printed circuit board (PCB) structures. Compound-semiconductor materials such as GaAs and InP also face recovery challenges. These materials are used in trace quantities, embedded within multilayer packaging and PCB structures, and almost entirely lost during mechanical and metallurgical waste electrical and electronic equipment (WEEE) processing [6].

Numerous studies show that gallium-bearing components typically end up diluted in mixed waste fractions, slag, or red-mud-type residues during primary production and recycling processes [4, 7]. Some studies further report that more than 90% of gallium losses occur during upstream production and refining stages before incorporation into electronic products [4].

These structural constraints in current electronic systems are summarized schematically in figure 1. This problem is intensified by the global inequity of e-waste flows. Driven in part by the high cost of regulated recycling, large volumes of e-waste are transferred from high-income countries to developing regions including Nigeria, India, Pakistan, and China through second-hand electronics trade and informal recycling channels [8–10]. Many recipient regions lack sufficient infrastructure for environmentally sound management of electronic waste [8–10]. As a result, informal dismantling, open burning, acid leaching, and uncontrolled dumping remain common practices and can release hazardous substances into surrounding environments [10–12]. Recycling workers are particularly vulnerable to exposure from toxic substances such as lead (Pb), cadmium (Cd), chromium (Cr), PCBs, and brominated flame retardants [12]. These conditions transform e-waste from a potential resource stream into a persistent environmental and public-health concern [6, 7, 12].

One emerging direction involves green materials, highlighted in the International Roadmap for Devices and Systems (IRDS) sustainability roadmap, which calls for materials with lower destructive economic impact, more process-friendly chemistries, and higher energy efficiency at the device level [2]. Although these discussions often focus on complementary metal-oxide-semiconductor (CMOS) and beyond-CMOS computing, similar sustainability challenges exist in optoelectronics. III–V epitaxy, plasma etching, and lithographic processing remain major contributors to environmental impact. In parallel, biodegradable and transient electronics present a fundamentally different paradigm. In these systems, substrates, dielectrics, conductors, and encapsulation layers are selected to undergo controlled disintegration after use, reducing long-term persistence and enabling environmentally benign disposal [6]. These approaches intersect with progress in organic electronics, natural-polymer substrates, and eco-designed materials that enable low-temperature, solution-processed manufacturing routes.

At the system level, semiconductor sustainability research increasingly employs life cycle assessment (LCA), material-flow analysis (MFA), and circular-economy (CE) modeling to quantify environmental impacts across fabrication, energy use, and end-of-life outcomes [1, 3].

Industry-level sustainability governance is also emerging across the semiconductor sector. Examples include the SEMI semiconductor climate consortium, imec (Interuniversity Microelectronics Center)'s sustainable semiconductor technologies and systems (SSTS) 'Virtual Fab' platform, and International Electrotechnical Commission TC113 standardization efforts for nano-enabled devices and materials reliability [2]. However, research across materials, manufacturing, recycling, and sustainability assessment remains fragmented, limiting a coherent lifecycle understanding of semiconductor and optoelectronic systems [13].

The key challenges, transition enablers, and long-term vision for this pathway are summarized in figure 2. Existing sustainability reviews in electronics often focus on individual lifecycle stages, specific material classes, or isolated recycling technologies. In contrast, this review adopts a systems-level perspective that integrates materials science, manufacturing, WEEE recycling chemistry, and LCA within a unified analytical framework. By tracing the interdependencies between upstream material decisions, fabrication processes, and downstream recovery outcomes, the review highlights the structural origins of III–V semiconductor dissipation and situates these challenges within broader circular economy and sustainability governance contexts. In doing so, it provides an integrated foundation for future cross-disciplinary research and policy development in sustainable semiconductor systems.

This paper adopts a structured narrative review methodology [14]. The review was conducted through structured searches of Google Scholar, ScienceDirect, and Web of Science, covering primarily peer-reviewed journal articles published between 2012 and 2026, while including foundational earlier studies where necessary. Search terms included combinations of 'e-waste recycling', 'degradable electronics', 'LCA', 'circular economy', 'compound semiconductor manufacturing', 'optoelectronics', 'environmental sustainability', and 'critical minerals'. Literature was selected based on relevance to III–V semiconductor materials, sustainable manufacturing, WEEE recycling chemistry, LCA methodology, and circular economy frameworks for electronics. Industry reports, standards, and policy documents were also included selectively where additional quantitative data on material flows, recycling practices, or recovery rates were required. Narratives were then built from the synthesis based on thematic classifications (sections 2–5), to address the key overarching purpose of this topical review, i.e. to review the innovation in compound semiconductors and optoelectronics and identify the structural limits and pathways to sustainability and circularity.

2. Sustainable material innovations for electronics and optoelectronics

2.1. Why material choices determine circularity

Across the entire lifecycle from raw material extraction to end-of-life, materials account for an estimated large share of energy demand, waste generation, toxic chemical usage, and environmental burden in manufacturing [2]. In the optoelectronics sector, where epitaxial III–V semiconductors, rare earth elements, and high-purity substrates dominate, the environmental footprint is often directly linked to the inherent characteristics of the materials themselves. For instance, elements such as Ga, In, and Ge not only require energy-intensive extraction but are increasingly recognized as emerging environmental contaminants due to their persistence and limited recyclability [3]. Rare earth usage across LEDs, laser diodes, photodetectors, and display technologies further couples optoelectronics with geopolitical constraints and unsustainable mining practices [15].

Circularity in semiconductor production cannot be achieved solely through downstream recycling innovations; instead, it requires upstream redesign of material systems to minimize toxicity, simplify

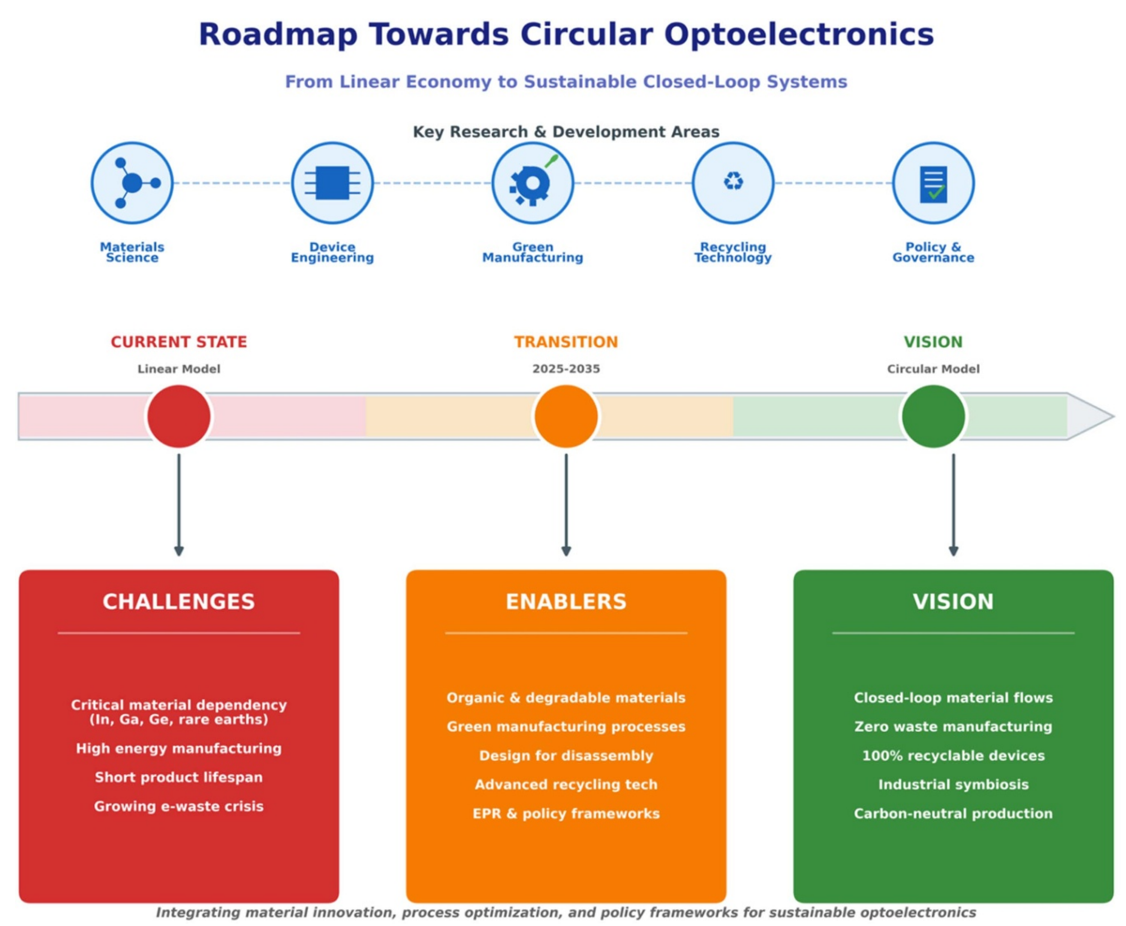

Figure 2. Roadmap illustrating the transition from linear to circular optoelectronic systems and the key technological innovation and policy enablers required. The color-coded framework highlights the progression from current sustainability challenges toward future circular optoelectronic systems enabled by advances in materials, manufacturing, recycling, and governance.

recovery, or enable natural degradation. This aligns with the IRDS vision for beyond-CMOS and sustainable semiconductor technologies, which identifies green materials, low-temperature processing, and reuse-enabled device architectures as foundational pillars [2]. In this context, emerging material classes organic semiconductors, biodegradable platforms, dissolvable packaging, and recyclable substrates offer transformative opportunities for optoelectronics.

Organic and polymeric materials reduce dependence on critical raw materials (CRMs) and support low-energy, solution-processed fabrication routes, as widely demonstrated in organic optoelectronics [6]. Moreover, recent work [16], shows that key organic semiconductors and conductors can be recovered through solvent-based end-of-life processes.

Biodegradable and transient materials provide pathways for fully disappearing systems, especially in short-lifetime optoelectronic devices such as transient sensors, wearable photodetectors, and implantable photonic systems [6]. Dissolvable packaging technologies offer alternative pathways for chip-level reuse [17].

Thus, material innovation can be the primary enabler of circular semiconductor and optoelectronic design. The remainder of this section reviews how specific material systems contribute to sustainable manufacturing, improved recyclability, and reduced environmental burdens, grounded in recent technological progress across electronics and optoelectronics.

2.2. Organic electronics as low-temperature and low-waste platforms

Organic electronics including organic LEDs (OLEDs), organic photovoltaics (OPVs), and organic field-effect transistors (OFETs) have emerged as promising platforms for sustainable optoelectronic technologies. Their intrinsic advantages stem from solution processability, low-temperature fabrication ($<$200 °C), mechanical flexibility as highlighted by [6]. These characteristics directly reduce the environmental burden associated with epitaxy, high-temperature vacuum deposition, and rare-metal consumption common in III–V and oxide electronic systems.

Organic optoelectronic materials provide a route to eliminate some of the most environmentally intensive steps in semiconductor fabrication. For example, solution-based photonic and electronic inks can be printed through scalable, additive manufacturing techniques such as roll-to-roll coating or inkjet printing, enabling high material utilization and minimal waste [6, 18, 19]. Compared with sputtering or metal-organic chemical vapor deposition (MOCVD) used in traditional optoelectronics, these methods rely on significantly lower energy inputs and avoid complex toxic emission control. Furthermore, many organic semiconductors are compatible with recyclable substrates or biodegradable platforms, allowing integration into broader circular manufacturing strategies [2].

Previously has shown that polymer substrates, conductive layers, and semiconducting films could be selectively delaminated and recovered through solvent-triggered dissolution. Thus enabling multiple reuse cycles with minimal performance loss [16]. This closed-loop approach is particularly relevant for flexible displays, wearable optical sensors, and disposable optoelectronic patches, where device turnover is rapid and the required performance can be achieved with the alternative technology.

Organic electronics also reduce reliance on CRMs. OLEDs, OPVs, and OFETs can be fabricated without indium tin oxide (ITO), gallium compounds, or rare-earth phosphors frequently used in high-performance optoelectronics [1]. By reducing CRM dependency, organic platforms directly address geopolitical supply risks and environmental pressures associated with rare earths mining [20].

Nevertheless, organic materials face performance limitations that constrain their adoption in high-end optoelectronics. Issues such as lower charge mobility, limited operational lifetime, oxygen/moisture instability, degradation under high-intensity illumination, and limited commercial scalability beyond niche applications remain significant challenges. For optoelectronic applications such as lasers, high-speed photodetectors, or power emitters, organic materials cannot yet match the performance of III–V semiconductors. Despite these limitations, their role in environmentally benign, low-cost, and recyclable electronics is increasingly strategic, especially for applications where ultra-high performance is not essential. However, the synthesis of many high-performance organic semiconductors involves multi-step chemical processes using hazardous solvents and reagents, and the full lifecycle environmental burden of organic electronics relative to conventional III–V systems has not yet been comprehensively quantified through LCA.

2.3. Biodegradable and transient materials for eco-friendly devices

Biodegradable and transient electronics represent a radical material strategy for minimizing e-waste by enabling devices to decompose naturally after use [6]. Provides a comprehensive overview of biodegradable substrates (cellulose, silk, polylactic acid), transient conductors (Mg, Zn, Mo), and organic electronic materials including conductive polymers such as poly(3,4-ethylenedioxythiophene) (PEDOT) which together form the materials foundation for emerging transient optoelectronic systems.

For optoelectronics, biodegradable substrates such as cellulose nanofiber films or silk fibroin offer good optical transparency, mechanical flexibility, and compatibility with organic emitters or photodetectors. Their ability to decompose through enzymatic or hydrolytic mechanisms makes them particularly suited for temporary optical sensors, implantable photonic systems, and short-lifetime environmental monitoring nodes. These materials reduce end-of-life burdens by eliminating the need for energy-intensive mechanical or chemical recovery processes.

Biodegradable conductors such as magnesium (Mg) and zinc (Zn) provide electrical pathways that naturally dissolve under physiological or environmental conditions, enabling fully transient interconnects and circuit components. In parallel, biodegradable or natural-material emitters have demonstrated transient light-emitting devices, underscoring the feasibility of short-lifetime optoelectronic systems with no long-term residue. Conductive polymers such as PEDOT, while not themselves fully degradable, serve as biocompatible and flexible electrode materials that can be integrated into biodegradable device architectures [6].

Equally important is the emerging class of biodegradable semiconductors, including natural pigments, organic charge-transfer complexes, or engineered polymers designed to decompose under mild conditions. Their optical absorption and emission properties make them candidates for transient OPVs, optical sensors, and environmentally benign displays.

The dissolvable packaging concept introduced by [17] enables the recovery and reuse of integrated circuits through water- or acetone-triggered dissolution of poly(vinyl alcohol) (PVA) or acrylonitrile–butadiene–styrene (ABS) packaging. By allowing commercial microcontrollers and other commercial off-the-shelf (COTS) chips to be extracted intact and redeployed in secondary applications, this approach reduces resource consumption and alleviates supply-chain stress without relying on hazardous decapsulation processes. While [17] focus on microcontroller-level COTS devices, the same dissolvable packaging strategy could in principle be extended to optoelectronic ICs used in display or sensing modules.

Apart from these advances, biodegradable optoelectronics still face important limitations. Biodegradable substrates such as cellulose and silk exhibit limited thermal stability and moisture sensitivity, restricting their use primarily to low-power and ambient-condition applications. Operational lifetimes are also significantly shorter than those of conventional electronic systems, limiting suitability for long-term infrastructure and sensing deployments. Overall, biodegradable and transient materials remain promising for applications including wearable optoelectronics, distributed sensing, and resorbable medical devices where limited operational lifetimes are acceptable.

2.4. Substrate technologies and circularity trade-offs

Substrates constitute a substantial portion of materials used in compound semiconductor and optoelectronic manufacturing. Their recyclability and associated waste profiles significantly influence the environmental footprint of device production. Silicon currently benefits from the most established wafer recovery and reclaiming systems, enabling limited lifecycle extension under controlled manufacturing conditions [1]. Wafer reclaim, kerf recycling, and repolishing allow partial material retention within manufacturing loops. However, once silicon devices are embedded within complex multi-material packaging systems, functional semiconductor-grade recovery at end-of-life remains extremely limited.

Germanium offers moderate recyclability, though contamination risks and cost barriers limit recovery [21]. Its increasing use in IR photodetectors, multi-junction photovoltaics, and next-generation optoelectronic substrates increases the urgency of developing Germanium-specific recycling routes [3]. Recent work on electrochemically porosified Ge substrates has demonstrated that annealed porous-Ge structures can act as high-quality templates for III–V epitaxy while embedding a controlled mechanical break layer a few micrometers below the surface [22]. After growth and device processing, the III–V stack can be mechanically lifted off at this porous layer, enabling reuse of the Ge wafer and a substantial reduction in germanium consumption for multijunction solar cells and other Ge-based optoelectronic platforms [22].

Moreover, III–V compound semiconductor substrates (GaAs, InP) pose a major challenge for circularity. Their production is energy-intensive, uses hazardous precursors, and recycling options are extremely limited. Gallium and indium are also high-risk CRM elements with growing environmental concerns [3]. Recovery rates of Ga/In from end-of-life devices remain low, leading to persistent leakage into the environment and contamination through downstream processes.

Emerging recyclable substrates offer promising alternatives. Thermoformed renewable polymer substrates demonstrated by [23] enable flexible, mechanically robust PCBs in which the structural base is derived from renewable materials. These substrates not only reduce dependence on petroleum-derived polymers but also simplify recycling through thermomechanical reprocessing [23]. In addition, renewable substrates may also be suitable for low-temperature optoelectronic devices such as flexible photodetectors, wearable OLEDs, and conformable optical sensors.

Furthermore, the dissolvable packaging approach [17] is particularly useful for optoelectronic modules containing micro-LED drivers, photodiode amplifiers, or digital control ICs, where the semiconductor substrate may not be recyclable but the IC remains highly valuable. The key circularity-relevant attributes of the substrate and packaging materials discussed in this section are summarized in table 1.

Figure 3 summarizes a comparative assessment across major material classes, highlighting their sustainability advantages and constraints.

For optoelectronic device designers, these comparisons clarify a fundamental trade-off: performance vs circularity. III–V semiconductors remain irreplaceable for high-power, high-brightness, and high-speed optical applications [24]. However, sustainable material innovations, particularly organic, biodegradable, and recyclable platforms are increasingly viable for low-power, flexible, or short-lifetime optical systems. Thus, material selection should be informed not only by optical performance metrics but by lifecycle environmental considerations and device longevity.

3. Sustainable semiconductor manufacturing

3.1. Sources of environmental burden in semiconductor manufacturing

The major environmental hotspots discussed in section 3.1 are summarized schematically in figure 4. Across multiple empirical assessments, several process-level and system-level hotspots consistently dominate the upstream impacts of chip fabrication. Cleanroom facilities, in particular, are widely recognized as among the most energy-intensive environments within semiconductor fabs. This is largely attributable to the stringent particle, temperature, and humidity controls required to support advanced lithography

Table 1. Comparative assessment of substrate and packaging materials used in semiconductor and optoelectronic systems, evaluated across key circularity-relevant attributes.

Material	Performance	Recyclability	CRM risk	Circularity potential
Silicon	High; mature CMOS/PV technology	Moderate; wafer reclaim established in manufacturing, limited post-consumer recovery	Low	Moderate
Germanium	High; IR optics, multi-junction PV, epitaxial substrate	Moderate; 30%–60% recovery in bulk applications; negligible from post-consumer electronics	High	Moderate (bulk applications only)
GaAs/InP	Very high; high-speed, high-power optoelectronics	Very low; structurally dissipative in WEEE streams	Very high (Ga, In)	Very low
Renewable polymer substrates	Moderate; suitable for flexible, low-power devices	High; thermomechanical reprocessing feasible	Low	High
Dissolvable packaging (PVA/ABS)	Moderate; enables IC reuse	High; solvent-triggered dissolution enables component recovery	Low	High

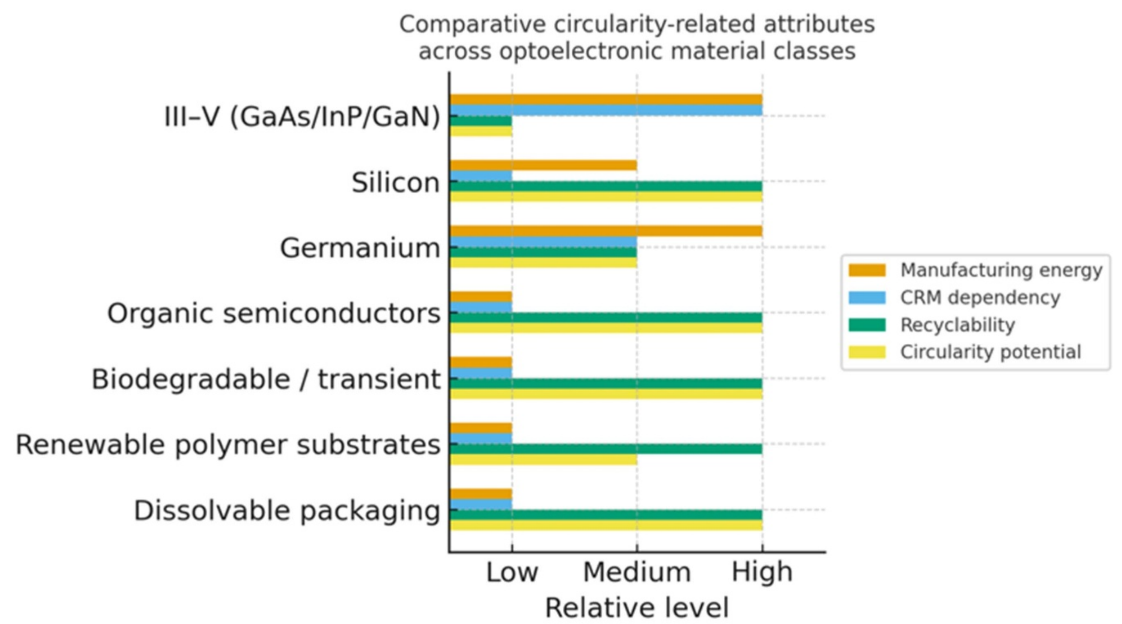

Figure 3. Qualitative comparison of circularity-related attributes across optoelectronic material classes, including manufacturing energy demand, critical raw material dependency, recyclability, and overall circularity potential.

processes, which impose significant and continuous loads on heating, ventilation, and air conditioning (HVAC) and air-handling systems. Recent analyses of semiconductor manufacturing facilities and cleanroom energy management practices consistently identify HVAC subsystems as major contributors to cleanroom-level energy demand [16, 17].

Chemical and water usage represent a second major environmental hotspot. A recent survey of 28 semiconductor manufacturers reported water withdrawals of 7.89×10^8 m^{-3} in 2021, with ultrapure water (UPW) usage averaging 5–8 l per cm^2 of processed wafer area [25]. This volume exceeds the total annual freshwater consumption of many mid-sized countries, underscoring the scale of water dependency in semiconductor manufacturing [25]. Wafer cleaning alone involves numerous sequential steps per device layer, relying on a wide range of acids, bases, and organic solvents. As node scaling increases

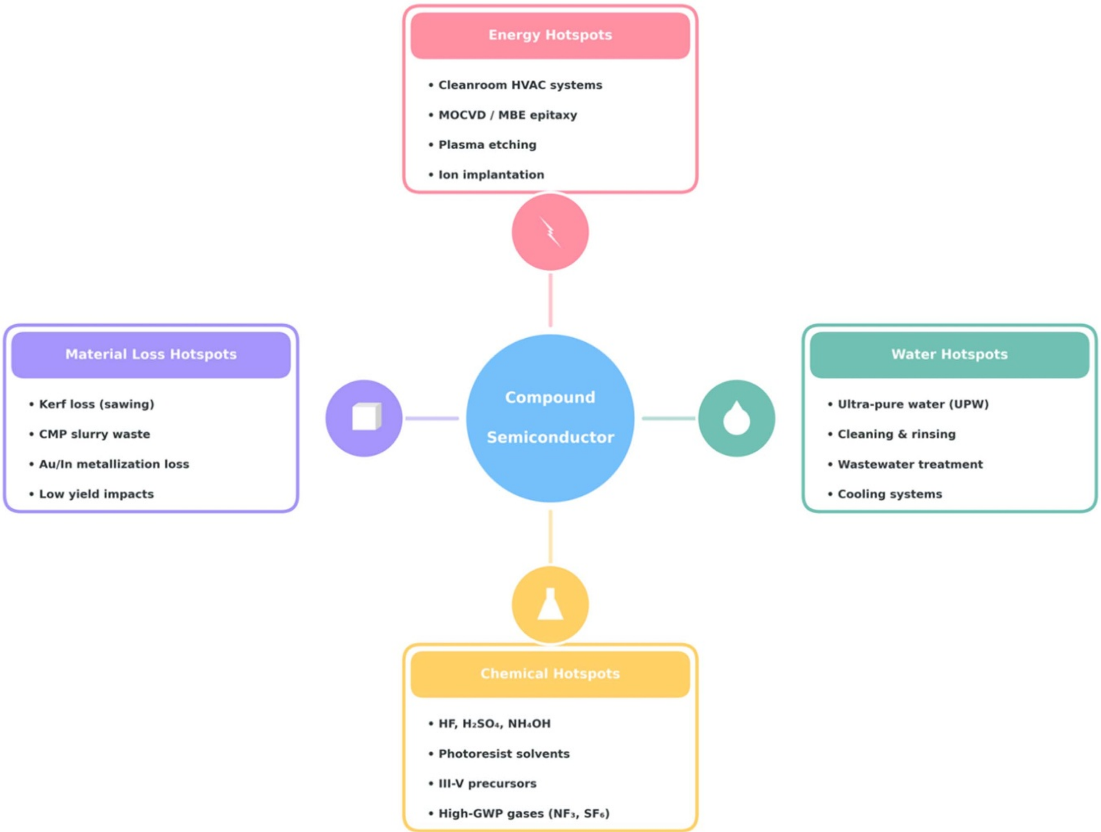

Figure 4. Process-level environmental burden categories in compound semiconductor manufacturing, highlighting representative energy-, water-, chemical-, and material-intensive fabrication stages. The color-coded categories distinguish different classes of sustainability impacts relevant to compound semiconductor production.

surface sensitivity and pattern density, lithography and etching steps also drive solvent consumption and generate complex waste streams. Traditional wet etching processes remain essential in several applications yet present significant occupational and environmental hazards, motivating research into greener chemistries [26].

Material loss is another constraint, particularly for III–V and Ge wafers, where reclaim and recycling remain limited. Wafer slicing and backside thinning introduce significant kerf loss. Silicon wafers can commonly be reclaimed with >90% material recovery [27], but GaAs and InP wafers generally cannot be reclaimed because their lattice quality degrades irreversibly after device processing and etching. Yield-related impacts, frequently overlooked, magnify these burdens: when device yield is low, all upstream energy, water, and chemical inputs are effectively multiplied per functional chip [28].

Finally, semiconductor manufacturing depends heavily on hazardous and resource-critical process gases and precursors, including hazardous organometallic precursors and high-global-warming-potential etch gases. These chemicals pose major safety challenges and are responsible for a substantial share of Scope 1 greenhouse gas emissions from fabs [29]. Resource criticality assessments have also identified Ga, In, Ge and W as high-risk elements due to their by-product supply chains, geopolitical concentration and lack of suitable substitutes [30]. The hotspots identified in this section establish the environmental basis for the mitigation and sustainability strategies discussed in section 3.3.

Environmental burdens differ substantially between silicon fabs and III–V compound semiconductor fabs. Silicon fabs benefit from mature process controls, established solvent-recycling infrastructure, and economies of scale that support investment in waste treatment systems. In contrast, III–V fabs typically operate at lower production volumes and rely heavily on MOCVD-based epitaxy using toxic hydride precursors that are absent from conventional silicon processing. III–V systems also face greater substrate reclaim limitations because lattice quality is often irreversibly degraded during device fabrication and etching processes.

3.2. High-impact processes in traditional semiconductor manufacturing

Among these manufacturing processes, epitaxial growth stands out. MOCVD and molecular beam epitaxy (MBE) for GaAs, GaN, and InP require high temperatures, large V/III ratios, and hazardous hydride precursors, resulting in high energy intensity and substantial emissions of arsine, phosphine and ammonia-derived effluents [31]. Even when low-temperature techniques such as plasma-assisted MBE or migration-enhanced epitaxy are applied, long deposition times and vacuum overheads maintain a large environmental burden [32].

Lithography and pattern transfer are another major hotspot. Photoresists and developers remain dominated by petrochemical-derived polymers and organic solvents, and billions of liters of propylene glycol monomethyl ether acetate (PGMEA), N-Methyl-2-pyrrolidone (NMP) and Isopropyl Alcohol (IPA) are consumed annually across the industry. Recent advances in green or water-based photoresists provide promising alternatives but remain at early technology readiness level (TRL) for high-volume production [33]. Meanwhile, extreme ultraviolet (EUV) lithography has intensified the sustainability challenge: EUV scanners require extreme illumination intensities, sub-2 nm resist performance, and high-purity hydrogen for tin debris mitigation, all of which increase electricity demand [34].

Wet etching and cleaning processes continue to rely on HF, HCl and H_2SO_4, generating large waste streams that require energy-intensive neutralization. CMP steps further contribute slurry waste containing colloidal silica, ceria, or alumina and trace metals. Despite improvements in slurry reuse and filtration, CMP remains a major generator of non-recyclable waste [35]. Deposition processes such as atomic layer deposition (ALD), chemical vapor deposition (CVD) and physical vapor deposition also present sustainability challenges. Although ALD enables atomic-scale precision, it requires repeated precursor pulsing and purging, making it one of the most energy- and gas-intensive thin-film technologies, prompting calls for greener precursors and spatial ALD configurations [36].

Packaging and assembly add additional layers of environmental impact through mold compounds, epoxy underfills, solder pastes, organic laminates, and wirebond metals. Gold and palladium remain critical materials with high embodied energy, while epoxy-based materials inhibit recyclability and complicate component disassembly [37]. As advanced packaging (3D ICs, chiplets, hybrid bonding) proliferates, material complexity continues to increase, challenging efforts to design recyclable or low-impact assembly flows.

3.3. Sustainable manufacturing strategies: energy, water and chemical reduction

Most research and industrial initiatives focus on reduction of the environmental burden of semiconductor manufacturing by redesigning processes around lower temperature, lower waste and higher resource efficiency. Low-temperature epitaxy represents a major direction. Plasma-assisted MBE, high-density radical sources, and radical-enhanced MOCVD enable epitaxial growth at reduced temperatures without significantly compromising film quality. These approaches can lower thermal energy demand and support deposition on thermally sensitive substrates [31]. Low-temperature homoepitaxy of β-Ga_2O_3 at 600 °C further demonstrates how material systems traditionally requiring extreme temperatures can potentially be shifted into more energy-efficient regimes [38].

A parallel direction involves greener lithography. Water-based photoresists derived from bio-sourced polymers such as chitosan have demonstrated compatibility with 193 nm deep ultraviolet lithography while eliminating large volumes of organic solvents and alkaline developers [39]. Mechanically peelable resists and dry-transfer lithography reduce solvent usage and simplify resist stripping, offering promising routes for solvent-free patterning [33]. Additionally, sustainable etching strategies such as eco-friendly glass etching chemistries or atomic-layer etching with minimized fluoride gas flows offer pathways to lowering chemical toxicity while maintaining nanoscale control [20, 22].

Water recycling has become a central industrial priority, and leading fabs now integrate multi-stage UPW reclaim loops capable of recovering up to 70%–85% of rinse water. Chemical reduction is driven by process simplification: fewer lithography and etch steps through EUV lithography, selective epitaxy, and self-aligned device architectures can meaningfully reduce cumulative chemical demand [34].

Finally, sustainable precursor development such as low-hazard ALD precursors, metal-organic alternatives with reduced decomposition energy, and precursor bottle return systems represents an important strategy for reducing chemical waste and Scope 1 emissions [36]. Beyond process optimization, material-platform redesign also offers a complementary pathway toward lower-impact manufacturing. Moreover, emerging thin-film and flexible electronic platforms reduce substrate material intensity by orders of magnitude. Organic electronics, ultrathin inorganic membranes, and 2D materials can be deposited onto

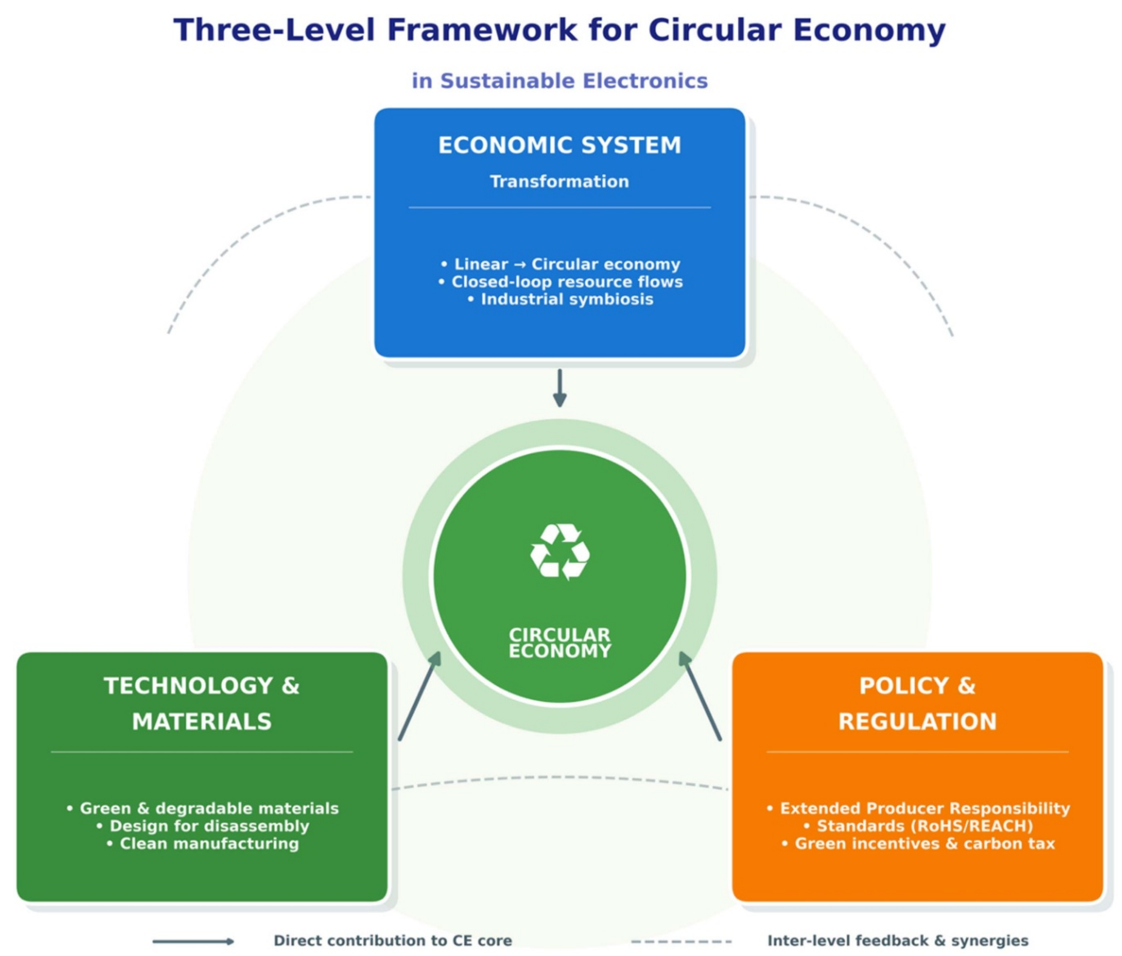

Figure 5. Three-level framework for circular economy implementation in sustainable electronics, illustrating interactions between macro-level economic transformation, micro-level materials and technology design, and governance-driven policy mechanisms.

polymer, metal-foil, or glass substrates at low temperatures, substantially lowering energy and material intensity. These platforms also enable large-area applications with inherently lower embodied environmental impacts compared to conventional wafer-based fabrication [33–35].

3.4. Precursor, chemical and solvent recycling pathways

Closed-loop recycling within the fab is increasingly recognized as essential for reducing reliance on virgin materials and minimizing hazardous waste. In MOCVD processes, precursor bottle return and purification cycles for TMGa and TMIn enable significant recovery of high-value organometallics and reduce waste gas volumes associated with cylinder disposal. Solvent recycling has become viable through distillation and membrane-based purification, and IPA, acetone and PGMEA can now achieve multiple reuse cycles with minimal purity loss [40].

CMP slurry recycling, although technically challenging due to nanoparticle agglomeration and metal contamination, has shown progress through sedimentation, filtration and chemical rebalancing methods that allow partial reuse of slurry components. Metal reclaim represents another high-impact recycling opportunity: sputtering targets, polishing pads and wafer metallization steps produce recoverable gold, copper, silver and platinum, and industrial reclaim systems routinely achieve recovery rates above 90% for precious metals [37].

These internal circular loops are essential complements to downstream e-waste recycling and demonstrate how manufacturing can internalize resource recovery early in the product lifecycle. The multi-level interactions required to enable this transition are conceptualized in figure 5.

3.5. Implications for circular semiconductor manufacturing

The analysis across sections 3.1–3.4 indicates that circularity constraints originate upstream rather than at end-of-life. III–V materials face intrinsic sustainability barriers arising from high-temperature epitaxy, toxic precursors and non-reclaimable substrates. Silicon and germanium demonstrate partial circularity through well-established reclaim and recycling flows, while emerging organic and thin-film platforms present opportunities for inherently low-waste electronics. A future transition toward circular semiconductor manufacturing therefore requires interventions at the process-design level reducing temperature and chemical intensity, increasing reclaimability, designing precursors for safe recovery and minimizing lithographic and etching steps. These strategies establish the essential manufacturing foundation upon which downstream e-waste recovery and material recirculation, discussed in subsequent sections, must build.

4. E-waste recycling and resource recovery

This section examines how upstream material and manufacturing constraints translate into systematic material loss at end-of-life, with particular attention to compound semiconductor-containing devices.

4.1. Overview of E-waste composition and recycling challenges

Although compound semiconductors represent a relatively small fraction of total electronic waste by mass, their presence in high-performance optoelectronic and photonic systems is rapidly expanding. Meanwhile, electronic waste as a whole has emerged as one of the fastest-growing and least circular material streams globally. Recent assessments estimate that annual e-waste generation has risen from 34 Mt in 2010 to more than 62 Mt in 2022, and is projected to exceed 82 Mt by 2030, outpacing formal recycling capacity by nearly a factor of five [5]. This expansion is driven by rapid device turnover, shortening product lifespans, and the proliferation of complex consumer electronics whose material heterogeneity directly undermines recyclability. Modern electronic and optoelectronic devices typically contain over 60–70 chemical elements, spanning metals, polymers, ceramics, adhesives, coatings, rare earths, and compound semiconductors [41]. Such compositional diversity means that end-of-life processing must contend not only with multiple material classes but also with intricate micro-scale architectures in which these materials are tightly bonded, laminated, encapsulated, or co-sintered.

This design paradigm optimized for functionality rather than circularity has been identified across materials-science literature as a core structural barrier to sustainable resource recovery. This upstream origin reflects the fact that stable composites, irreversible cross-linked polymers, and atomically engineered semiconductors hinder effective separation in downstream waste systems [42]. In particular, composite architectures used in PCBs, IC packaging, multilayer touchscreens, and advanced optoelectronic assemblies are hard to recycle, as individual layers cannot be separated without destructive chemical or thermal treatment that disperses critical materials into low-grade residues [39, 43].

CRMs such as Ga, In, and Ge exemplify this structural mismatch. They appear in electronic products at milligram- to ppm-level concentrations, embedded within III–V semiconductor materials, functional layers such as transparent conductive oxides, and integrated optoelectronic devices including LEDs. Material flow analyses reveal that the vast majority of these elements dissipate throughout the value chain, with only trace quantities reaching end-of-life products. These amounts are too dilute and too deeply encapsulated within packaging architectures for economically viable recovery [4]. Although hydrometallurgical, solvometallurgical, and thermal routes successfully extract Au, Cu, Pd, and Ag from PCB-rich fractions, they offer no viable pathway at scale for ultralow-grade Ga, In, or Ge input streams [44].

Compounding the materials-science barriers are significant systemic and socio-economic constraints. Globally, only 17%–20% of e-waste enters formal recycling channels, while the vast majority is processed in informal sectors that rely on manual dismantling, open burning, acid leaching, and uncontrolled dumping [45]. These practices selectively recover high-value metals while destroying or dispersing all other material fractions including semiconductors, engineered polymers, and rare elements into the environment. Emerging contaminants research indicates that dissolved Ga, In, and Ge species exhibit mobility in aquatic systems, making their dissipation not only a resource-loss issue but also a long-term ecological risk [3].

Together, these factors illustrate a reality: the current e-waste system was not designed to recover the critical functional materials that underpin modern electronics. Its infrastructure, economics, and regulatory structures were built around high-volume base metals, not trace-level semiconductors. As a result, recovery challenges arise not from technological gaps alone but from deep misalignment between device design, material composition, and end-of-life processing capabilities.

If silicon-based electronics already face structural end-of-life limitations, the expansion of III–V-based optoelectronic systems risks further entrenching these linear material flows unless design-for-circularity principles are implemented at the upstream stage.

4.2. How modern E-waste systems actually work

Understanding why critical materials are lost requires examining how real e-waste recycling systems function. Across regions, the dominant workflow follows a broadly uniform sequence: collection, dismantling, mechanical size reduction, physical separation, and metallurgical refining, yet each stage progressively reduces the feasibility of semiconductor recovery.

The first bottleneck emerges at collection, where national averages range from 11% to 25% even under advanced policy regimes such as the WEEE Directive [46]. The UK, for example, generates 23.9 kg of e-waste per capita the world's second highest but formally collects only ∼17% of its WEEE, with the remainder entering dissipative flows, residual waste streams, or informal resale and export channels [47]. Because only collected material can undergo any form of controlled recycling, critical materials embedded in the uncollected fraction are entirely lost.

In the second stage, manual dismantling targets only large, economically valuable components such as power supplies, aluminum housings, heat sinks, and copper-rich wiring. ICs, LEDs, and optoelectronic dies remain embedded in PCBs, encapsulated under epoxy molding compounds, underfill, solder, and multilayer laminates. Studies consistently show that current large-scale industrial dismantling practices do not separate packaged semiconductor devices into recoverable material fractions, and that Ga-bearing components are not systematically identifiable within existing e-waste recycling streams [4].

Material destruction accelerates during mechanical shredding, where devices are fragmented into centimeter-, millimeter-, and eventually micron-scale particles. In conventional, non-selective recycling workflows, this step transforms highly engineered architectures into heterogeneous mixtures of metals, ceramics, glass, thermoset polymers, brominated resins, adhesives, and semiconductor fragments. Once GaAs or InP contained within packaged devices is comminuted, these materials are dispersed into shredder fines, where their effective concentration typically falls below levels required for selective and economically viable recovery [44].

Following shredding, physical separation methods (including magnetic sorting, eddy-current separation, air classification, electrostatic separation, and optical sorting) are primarily used to concentrate Fe, Cu, Al, and plastics. These processes are not designed to isolate semiconductor materials, which typically remain trapped within mixed fines or bonded composites. PCB pyrolysis and pyro-hydro hybrid systems can recover energy through pyro-oil or syngas and generate metal-rich residues; however, under conventional operating conditions semiconductors are largely fragmented into char or dust, resulting in negligible recovery of Ga, In, or Ge [48]. Recent studies have shown that higher recovery efficiencies can be achieved only when bulk shredding is bypassed through specialized pre-processing routes, such as selective disassembly or controlled thermal delamination applied to narrowly defined waste streams [39, 42, 44, 49].

Finally, in pyrometallurgical refining, metals are recovered by smelting concentrated PCB fractions [48]. However, gallium and indium partition predominantly into slag phases, as experimentally observed in copper smelters, while arsenic volatilizes meaning III–V materials are completely lost from the resource cycle [4]. Hydrometallurgical refining then selectively extracts Au, Cu, Pd, and Ag, but the dilute, mixed semiconductor residues fall outside the process envelope.

In summary, each stage of the current e-waste system is primarily optimized for the recovery of bulk and precious metals rather than functional semiconductor materials. Collection losses remove critical materials before processing begins, while subsequent dismantling and shredding stages often overlook semiconductors and destroy the physical integrity required for component-level recovery. As a result, sorting systems rarely isolate semiconductor particles effectively, and metallurgical refining frequently dissipates gallium, indium, and germanium into slag, fumes, or char. Consequently, existing recycling infrastructures remain poorly suited to the recovery of III–V semiconductors and other highly dispersed critical materials.

4.3. Why III–V semiconductors are non-recyclable under current systems

Multiple converging lines of evidence from materials science, industrial metallurgy, MFA, and experimental recycling studies suggest that III–V semiconductors behave as structurally dissipative materials under current industrial systems [4]. Once integrated into complex electronic devices, their recovery at meaningful industrial scale remains highly limited within existing e-waste recycling infrastructures [4].

Lifecycle analyses of gallium provide the clearest empirical demonstration [4]. Show that 93 ± 11% of all gallium used in the electronics value chain is lost before it ever reaches the consumer, with significant dissipation occurring during alumina production (33%), epitaxial wafer manufacturing (19%), and semiconductor device fabrication (26%) [4]. Of the gallium that does enter products, the majority is embodied in milligram-scale amounts typically 0.9–1.3 mg per integrated circuit far below the concentration thresholds at which metallurgical recovery is feasible. This extreme dilution is compounded by the fact that GaAs, GaN and InP are covalent crystalline compounds requiring high-energy chemical separation steps that cannot be selectively applied to mixed WEEE streams.

Even when thermal liberation is attempted at 250 °C–550 °C, the resulting Ga-rich residue contains 20–28 wt% arsenic and significant Cu/Au contamination, illustrating that no practical purification pathway exists for such mixed fractions [4]. These findings confirm that the chemistry of III–V semiconductors, combined with their low mass loading and entanglement in composite packaging, is fundamentally incompatible with end-of-life extraction. As highlighted in recent environmental studies, their eventual release into soils and waters as dissolved Ga(III) and In(III) species represents an emerging contamination concern rather than a resource loop [3].

Collectively, these studies show that III–V semiconductors exhibit very limited circularity under current production and waste-treatment systems. Their atomic-level purity requirements, chemical stability, and integration into complex multi-material devices create major barriers to economically viable end-of-life recovery.

As a result, Ga and In in microelectronic and optoelectronic systems can be regarded as dissipative critical materials (i.e. technology-critical elements that are irreversibly lost to the materials cycle during normal use and end-of-life processing) because they are highly prone to loss during use and end-of-life processing. Meaningful circularity is therefore more likely to depend on upstream strategies such as material substitution, design-for-disassembly, and broader system-level redesign.

4.4. Recovery pathways for recoverable materials

In contrast to III–V semiconductors, certain material classes in electronic waste exhibit more established or economically viable recovery pathways, although often only under specific concentration or separation conditions. These include silicon in wafer or photovoltaic formats, germanium in specific high-concentration applications, precious metals and base metals that benefit from high intrinsic value or favorable metallurgical chemistry. Examining these comparatively recoverable materials clarifies why semiconductor-grade Ga and In in microelectronics behave fundamentally differently from materials that successfully circulate.

Silicon represents one of the most mature cases of circularity among functional electronic materials. Wafer reclaim has been practiced for decades within semiconductor manufacturing, where damaged or surplus wafers are chemically etched and polished for reuse in process monitoring and equipment calibration. In parallel, the photovoltaic industry has developed specialized recycling routes that thermally delaminate EVA encapsulants, liberate crystalline silicon cells, and recover Al and Ag metallization. Recent hydrometallurgical processes achieve >95% Si recovery and enable conversion back into solar-grade feedstock in some cases [27]. The key enabler is that Si appears in bulk form, at high purity, and is physically accessible, unlike semiconductors encapsulated inside ICs.

Germanium offers a second example of partial circularity. While Ge in microelectronic components is as unrecoverable as GaAs, the element maintains moderate recovery rates typically 30%–60% in sectors where it is used in concentrated applications, such as infrared optics, fiber-optic systems, catalysts and copper indium gallium selenide photovoltaic absorbers [1]. In these cases, germanium can be recovered following targeted pre-treatment and hydrometallurgical processing, reflecting both favorable chemistry and sufficient material loading [45, 49]. Partial circularity is also observed in tightly controlled industrial loops involving high-grade manufacturing residues. For example, spent sputtering targets containing Ga–Ge alloys can be efficiently recycled using vacuum distillation or hydrometallurgical separation [50]. Crucially, these recovery pathways rely on pre-separated, high-purity feedstocks and do not extend to post-consumer electronics, where germanium occurs only at trace levels and is irreversibly dispersed during end-of-life processing. Similarly, although certain commercial services reclaim damaged or surplus InP wafers within controlled manufacturing environments, such recovery remains restricted to pre-device-processing materials and does not extend to mixed post-consumer electronic waste streams.

The most successful recovery category remains precious metals, which dominate the economic landscape of e-waste recycling. Their concentrations often exceed those of primary ores, making recovery economically attractive, and mature hydrometallurgical and smelting infrastructures routinely achieve recovery rates above 90% [10, 44]. Importantly, this same infrastructure is optimized for bulk and precious metals rather than functional semiconductors, causing Ga and In to partition into slag rather than recyclable metal phases.

Economic viability presents a structural barrier that compounds the technical challenges outlined above. Gallium content in integrated circuits typically falls in the range of 0.9–1.3 mg per device, far below the concentration threshold at which hydrometallurgical recovery becomes cost-effective [4]. As a result, reagent, energy, and processing costs can exceed the market value of recoverable gallium from mixed WEEE streams. Material flow analyses further show that 93 ± 11% of all gallium in the electronics value chain is lost before reaching end-of-life recycling stages, with an end-of-life recycling rate of less than 1% [4]. In the absence of policy mechanisms that internalize the strategic value of these materials, market forces alone provide limited incentive to develop dedicated Ga or In recovery pathways [4].

Overall, circularity in electronic waste systems is achieved primarily for materials that occur in high mass fractions, form chemically tractable phases, or are embedded in dedicated recovery loops with clear economic incentives. While gallium and indium can be recovered from selected high-grade secondary sources, their recovery from post-consumer microelectronic devices remains limited, leading to their continued dissipation at end of life.

4.5. Chemical and hydrometallurgical recovery approaches

Chemical routes encompassing hydrometallurgy, solvometallurgy, electrochemical extraction and thermochemical processing form the scientific foundation of modern e-waste recycling. Across the literature, these processes demonstrate high efficiency for specific metal recovery scenarios, though their effectiveness diminishes substantially when confronted with heterogeneous, low-grade semiconductor-bearing waste fractions. Understanding their capabilities and limitations helps clarify the conditions under which chemical pathways can or cannot address the losses of Ga, In and Ge in ICs and LEDs.

Hydrometallurgy is the most widely implemented. Its lixiviants such as aqua regia, cyanide, thiourea, thiosulfate and chloride complexes are capable of selectively dissolving precious metals and copper at industrial scales [44]. The dissolved species can then be purified through solvent extraction, ion exchange, cementation or electrowinning. However, hydrometallurgical selectivity depends critically on the chemical accessibility and mass fraction of target metals. When applied to shredded PCBs, it effectively recovers Au, Ag, Pd and Cu; yet when applied to semiconductor-containing fines, recovery yields decline sharply as reagent consumption increases disproportionately. III–V materials resist dissolution under mild conditions, and attempts to dissolve GaAs or InP require aggressive chemistries that pose compatibility challenges with WEEE streams [51].

Solvometallurgical approaches, including ionic liquids and deep eutectic solvents, offer milder, tunable chemistries and reduced aqueous waste generation. Early demonstrations show that DES systems can dissolve copper or tin selectively and may extract indium from concentrated ITO waste [1]. Recent advances in triiodide ionic liquids have achieved remarkable results. For example, one study reported gallium recovery exceeding 97% and arsenic recovery exceeding 94% from GaAs under mild conditions (80 °C), with the ionic liquid maintaining effectiveness over six reuse cycles [52]. However these results were obtained using pre-purified semiconductor powders as feedstock. When applied to real-world e-waste where semiconductor particles are dispersed at milligram levels within multi-material matrices, the effectiveness of such systems remains to be demonstrated. The gap between laboratory-scale success with model materials and industrial applicability to heterogeneous WEEE streams represents a key challenge for future research.

Thermo-chemical processes notably pyrolysis address polymer removal while generating pyro-oil, syngas and carbonaceous char as energy products. Pyrolysis can concentrate metals by degrading organics, producing a residue amenable to downstream hydrometallurgy [44]. But semiconductor dies tend not to survive pyrolysis intact: they fragment into dust and char, where Ga, In and Ge become significantly diluted. Pyrolysis therefore facilitates metal liberation only for bulk metals; for III–V semiconductors, it may accelerate dissipation rather than enable recovery.

Bio-hydrometallurgy presents an environmentally benign alternative using Acidithiobacillus and related microorganisms to leach metals from finely milled waste. While promising for copper and zinc recovery from PCBs, bioleaching is too slow, too non-selective, and too sensitive to inhibitory plastics and flame retardants to be viable for semiconductor-bearing fractions [51]. Further development in microbial strain engineering and process optimization would be needed before bioleaching becomes viable for III–V recovery.

Collectively, chemical routes operate most successfully when waste streams contain concentrated, chemically accessible metals. Their effectiveness diminishes when target materials exist as microscopic, heterogeneous residues dispersed during dismantling and shredding. For III–V semiconductors specifically, the combination of ultralow concentration, encapsulation within complex packages, and thermodynamic stability presents substantial challenges for current extraction chemistries at industrial scale. Advances in upstream physical separation and pre-concentration may therefore be prerequisites for realizing the full potential of these chemical recovery technologies.

4.6. Emerging E-waste solutions for organic and biodegradable electronics

As conventional recycling systems prove incompatible with semiconductor-rich miniaturized electronics, new strategies aim to circumvent end-of-life challenges by altering the materials themselves. Organic, polymer-based and biodegradable electronics together with dissolvable or disassemblable packaging architectures represent a paradigm shift from 'recovering materials after failure' to 'designing materials for recovery'.

Recent advances demonstrate that organic conductors, semiconductors and gate dielectrics can be fabricated using polymers intentionally engineered for solubility or depolymerisation, enabling closed-loop material recovery without high temperatures or aggressive chemicals [8, 33]. Fully recyclable flexible devices have been produced using eco-friendly solvents such as water, acetone or anisole, illustrating that complete component recapture is achievable when architectures are designed with chemical reversibility in mind.

Complementing these developments, dissolvable chip packaging based on water-soluble binders or thermally triggered disassembly enables recovery of bare dies without shredding [17]. Such packaging dismantles via moisture exposure or mild heating, separating encapsulants from functional components while avoiding mechanical destruction. From a materials-science perspective, biodegradable substrates including cellulose nanofibres, silk fibroin, PLA, and other bio-derived polymers reduce reliance on landfill-persistent plastics.

These approaches currently target low-power flexible electronics, sensors, and transient devices rather than high-performance III–V optoelectronics. They do not resolve the dissipation of Ga and In from existing product streams. However, they demonstrate that circularity can be improved when end-of-life recovery is considered during material and device design.

4.7. systemic barriers to circular E-waste management

Beyond materials and technology, the global e-waste system is constrained by systemic, economic and institutional barriers that reinforce the dissipation of critical materials. These barriers act at every stage of the value chain from product design to consumer behavior to national policy [53].

Conflict minerals such as tin, tantalum, tungsten, and gold (3TG), which are widely used in PCBs, capacitors, and interconnect structures, have been linked to supply chains associated with conflict-affected regions, particularly the Democratic Republic of Congo [52, 53]. Recent regulatory frameworks and industry-led responsible sourcing initiatives have improved traceability and supplier auditing practices. However, significant challenges remain across complex multi-tier global supply networks.

A primary bottleneck is low collection efficiency. Even under established policy regimes, a substantial share of e-waste bypasses formal collection, and any material in these flows is effectively unavailable for controlled recovery. Because III–V-related elements occur at trace levels, small reductions in collection translate into disproportionate losses [47].

The dominance of informal recycling in many regions further accelerates dissipation. This reflects incentive structures rather than a lack of awareness: formal recycling is capital-intensive, whereas informal routes provide rapid income with low barriers to entry [45].

Economic non-viability is another critical barrier. DEMATEL analysis of the UK e-waste sector identifies lack of processing technology, insufficient economic return, lack of expertise, weak collection standards and low public awareness as the principal obstacles blocking circularity [47]. Even in advanced economies, no business model exists for recovering milligram-level critical materials. Chemical or metallurgical extraction of III–V semiconductors would consume far more energy and reagents than the value of the recovered material, making such processes structurally incompatible with market forces.

Technological barriers further compound these challenges. Existing industrial sorting technologies have limited capability to detect or separate III–V-bearing components, while standardized labeling systems for semiconductor content and dopants remain largely absent. In addition, shredding processes often destroy the physical integrity required for component-level recovery. The system is further constrained by fragmented policy frameworks, where responsibilities and incentives for design-for-recycling, extended producer responsibility, consumer return schemes, and material transparency remain inconsistently implemented across jurisdictions.

These systemic constraints interact with the technical factors outlined in sections 4.2–4.5, producing a unified outcome: until upstream interventions reshape how devices are designed, labeled, collected and processed, III–V semiconductors will continue to exhibit dissipative lifecycle behavior regardless of advances in recycling technologies.

5. LCA and circular economy integration

5.1. Role of LCA in evaluating electronics and optoelectronics

Section 4's findings indicate that III–V semiconductor dissipation is a structural effect of device design and end-of-life systems, not simply a technological recycling constraint. It suggests that the sustainability concerns in semiconductor-rich devices must be assessed across the whole lifespan. LCA and circular CE frameworks are thus critical tools for evaluating the environmental impacts, material dissipation, and possible leverage points beyond standard recycling [54]. Conventional assessments that focus solely on operational efficiency such as power consumption in display or lighting applications fail to capture the upstream impacts embedded in materials extraction, wafer production, epitaxy, lithography, or end-of-life losses. However, LCA provides the system-level visibility needed to quantify these burdens and situate semiconductor innovation within broader sustainability and circularity goals [23, 50, 55–57].

LCA results for semiconductor systems are highly sensitive to methodological assumptions. Functional units may be defined per wafer, per device, or per unit of delivered optical or electronic performance, limiting direct comparability across studies. Environmental impacts also depend strongly on system-boundary selection, particularly regarding whether upstream material extraction, use-phase energy consumption, and end-of-life recovery are included. Additional uncertainty arises from allocation methods for by-product critical materials such as gallium, indium, and germanium, whose environmental burdens can vary substantially depending on economic, mass-based, or system-expansion allocation approaches.

A key motivation for applying LCA to advanced electronics is the substantial environmental footprint of upstream material production [58]. Many high-performance optoelectronic devices rely on elements classified as CRMs whose extraction and refining involve high embodied energy, geological scarcity, and concentrated geopolitical supply risks [59]. System-level criticality analyses show that metals such as Ga, Ge, and In exhibit high vulnerability scores due to limited co-production pathways and low recycling rates [23, 54, 60]. The EU 2023 CRM report further highlights that CRM demand for optoelectronics and photonics is expected to grow sharply, yet recycling remains negligible ($<$1% for GaAs and InP) [61].

As discussed in section 3, manufacturing hotspots including cleanroom energy demand and high-intensity unit processes (e.g. lithography, etching and CMP) [62]. For materials such as germanium, recent LCAs demonstrate large variations in carbon footprint depending on whether the Ge is obtained from by-product zinc refining, coal fly ash, or secondary recycling [63]. These variations underscore the importance of LCA for comparing sourcing pathways and identifying opportunities for low-impact material substitution.

Beyond quantifying hotspots, LCA can inform materials and process decisions within semiconductor technology development [64]. It enables systematic comparisons between alternative substrates (e.g. GaAs versus Ge), different packaging or metallization schemes, low-temperature versus conventional epitaxy routes, or chemically intensive versus solvent-minimized lithography systems [58]. In addition, it also provides evidence for emerging sustainable manufacturing strategies such as precursor recovery, green solvent substitution, reduced-temperature growth, and wafer reclaim programs [56, 57]. This allows industry and policymakers to weigh trade-offs across environmental indicators rather than relying on single-metrics. As CE principles become increasingly central to sustainable electronics, LCA acts as a foundation for integrating environmental performance with circularity indicators such as recycled content, end-of-life recovery, and material circularity scores [65].

Despite its relevance, LCA coverage for advanced semiconductor materials especially III–V optoelectronic systems remains limited. Existing studies often focus on silicon photovoltaics, consumer electronics, or bulk metals, while detailed LCAs of GaAs, InP, GaN, or photonic integrated circuits are scarce, typically restricted to single-device case studies with inconsistent methodological boundaries. This gap presents a significant barrier to evaluating the true sustainability of next-generation optoelectronics. Strengthening LCA coverage for these technologies is therefore essential for guiding material selection,

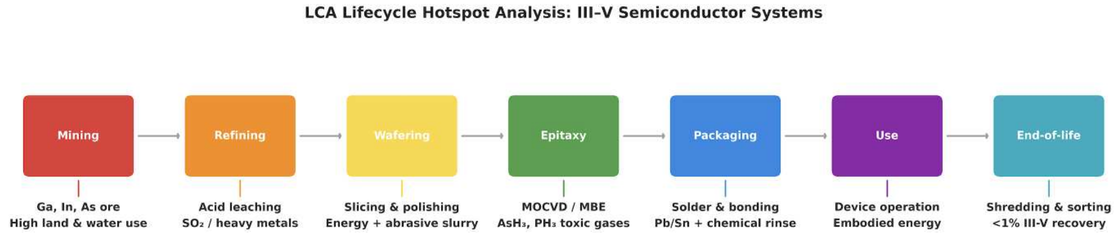

Figure 6. Lifecycle hotspot analysis for III–V compound semiconductor systems, identifying key environmental burdens across material extraction, manufacturing, use, and end-of-life stages. Hotspot descriptions indicate dominant impact drivers at each lifecycle stage.

identifying feasible pathways for circularity, and developing evidence-based policies for CRMs management. In this context, LCA functions not merely as an accounting tool but as a strategic instrument for shaping sustainable semiconductor innovation.

5.2. Environmental hotspots across semiconductor life cycles

The key environmental hotspots across the III–V semiconductor lifecycle are summarized in figure 6.

Building on the process-level hotspots identified in section 3, LCA studies consistently show that the environmental burdens of semiconductor and optoelectronic systems concentrate in three lifecycle stages, beginning with the upstream production of electronic-grade materials. Key elements such as Ga, In, and Ge are obtained as low-concentration by-products of zinc, bauxite, or copper refining, requiring highly energy-intensive hydrometallurgical or pyrometallurgical processing [23, 54]. Recent LCA studies demonstrate, for example, that primary Ge derived from zinc by-products carries a footprint of ∼852 kg CO_2-eq per kilogram of refined germanium crystals substantially lower than coal-derived Ge but still far higher than secondary Ge highlighting how environmental load is determined before wafer fabrication even begins [62].

The manufacturing stage represents the second dominant hotspot. Although the mechanistic drivers were detailed in section 3, multiple independent LCA studies consistently identify that epitaxy, lithography, plasma etching, CMP, and cleanroom operation collectively dominate mid-stream environmental impacts [66]. In III–V systems, epitaxy often exceeds the combined impacts of wafer production and packaging by an order of magnitude due to high-temperature operation, precursor decomposition energy, and the use of hazardous organometallic or hydride gases [54].

Use-phase burdens vary substantially by application. Lighting, display, and photovoltaic systems are dominated by operational electricity consumption, whereas lasers, detectors, and microelectronic devices exhibit comparatively small operational impacts relative to their substantial upstream embodied burdens [67]. This means that device-level efficiency improvements cannot compensate for the high environmental costs embedded in GaAs-, InP-, or Ge-based material systems [54].

End-of-life represents the final critical hotspot, as the complex multi-material integration of semiconductor devices results in near-zero functional recycling rates for Ga, In, and Ge [23, 54, 62, 68]. The implications of these end-of-life losses, and the structural barriers that underpin them, were analyzed in detail in section 4.

Concrete LCA evidence for III–V compound semiconductors remains limited, but recent studies are beginning to quantify these impacts at device and supply chain levels [69]. Developed a geospatial prospective LCA framework for InGaN and InGaP semiconductors across 80 international supply chain scenarios spanning 11 countries and four future time horizons to 2050. The study demonstrates that environmental impacts are strongly dependent on manufacturing geography, electricity mix, and supply chain configuration. Scenarios involving fabrication in the UK and USA consistently showed lower environmental impacts, while China-centered fabrication scenarios remained among the highest-impact pathways. The authors further identified epitaxial growth, substrate preparation, and electricity-intensive fabrication processes as major environmental hotspots requiring future process and supply chain optimization.

5.3. Circular economy principles applied to semiconductor systems

CE principles aim to decouple economic activity from the consumption of finite resources by keeping materials in circulation for as long as possible through strategies such as reduction, reuse, remanufacturing, recycling, and design for durability [70]. These principles have been widely adopted in sectors such as automotive, consumer products, and metals processing, where material flows are measurable, components are physically accessible, and recycling technologies are well developed [50, 63, 64]. Frameworks such as the material circularity indicator (MCI), provide structured methods for assessing circularity at product and system levels [65]. While these tools have proven effective for evaluating macroscopic material systems, their application to semiconductor and optoelectronic technologies reveals structural constraints. As a result, semiconductor systems differ fundamentally from conventional industrial products.

Nevertheless, CE principles can be selectively applied to semiconductor systems when materials and device architectures permit. Silicon offers as an example that wafer reclaim and kerf-loss recycling enable partial recovery of valuable materials in photovoltaic and microelectronic manufacturing [71, 72]. In addition, it also benefits from well-developed recycling infrastructure in downstream applications, supported by consistent material composition and a large global waste stream [73]. Germanium represents a second category of materials with potential circularity [74]. The LCA results demonstrate that secondary Ge sourced from photovoltaic scrap yields far lower environmental burdens than primary Ge derived from coal or zinc by-products. These findings suggest that closed-loop recycling has the potential to significantly reduce impacts if appropriate collection and processing pathways are developed [62, 66]. Organic and polymer-based electronic materials offer another route to circularity, given their low upstream energy demand and absence of CRMs, though durability and functional performance tradeoffs remain to be addressed [75].

At the industry level, coordinated circularity initiatives are beginning to emerge. The SEMI Circularity Working Group, established in 2023 and comprising approximately 49 member organizations, has collaborated with imec's SSTS program to develop a cross-industry framework for material circularity across the semiconductor value chain [64]. The framework identifies 69 materials prioritized according to criteria including CRM status, embodied global warming potential (GWP), and recovery feasibility. Indium is ranked among the highest-priority materials in the assembly and test segment, while gallium and germanium are identified as critical materials driving circularity concerns. However, the report also acknowledges that recovery infrastructure and localized collection systems remain underdeveloped, highlighting the gap between circularity ambitions and current implementation capacity.

5.4. Integrating LCA with circularity metrics

While LCA provides a rigorous framework for quantifying environmental burdens across the semiconductor lifecycle, it does not inherently account for how effectively materials circulate through the economy [76]. Traditional attributional LCAs evaluate energy use, emissions, and resource depletion. However, they lack indicators for recyclability, retention of material value, or the long-term availability of critical elements factors that are essential for assessing the sustainability of electronics and optoelectronics [77]. For GaAs or InP, environmental profiles are shaped not only by their embodied energy but also by structural factors such as co-production constraints, scarcity, and near-zero end-of-life recovery [68, 78]. Criticality assessments consistently show that these materials face high supply risks and low recycling rates, making environmental indicators alone insufficient for guiding sustainable technology choices [23, 54, 79].

Circular economy metrics help address this gap by introducing measures that reflect the extent to which materials remain in high-value loops rather than being dissipated [80]. The MCI, developed by the Ellen MacArthur Foundation and Granta Design, is one of the most widely adopted frameworks for evaluating circularity at the product and company level [81]. MCI integrates information on recycled content, component reuse, product lifetime, and end-of-life recovery efficiency into a single score between 0 and 1, where higher values indicate more restorative material flows [58, 82]. Complementary indicators such as material scarcity, supply chain risks, price volatility, and toxicity provide further insights into vulnerabilities that LCA alone does not capture [83–85]. These metrics are particularly relevant for semiconductors, where CRM dependencies and complex multi-material architectures limit practical recycling pathways [59].

However, the application of circularity metrics in semiconductor manufacturing is not straightforward. Reviews of sustainability barriers in high-technology value chains highlight that semiconductor facilities face unique obstacles compared with conventional manufacturing, including chemical complexity, high-temperature processing, and extremely low tolerance for impurities [55, 86, 87]. These constraints limit the feasibility of reusing process. Moreover, current recycling technologies are largely incapable of separating and purifying III–V elements at component end-of-life, meaning that even high MCI scores at the product design stage would not necessarily translate into real material recovery.

Despite these challenges, integrating LCA with circularity metrics yields a more comprehensive sustainability framework for evaluating semiconductor materials and manufacturing pathways [88]. Combining LCA and circularity metrics clarifies that recycled Ge is not only environmentally preferable but also strategically beneficial due to reduced supply risks something not evident from LCA alone [62, 74, 76]. Similarly, in silicon-based industries, wafer reclaim and kerf recycling illustrate how process-level interventions can improve both environmental performance and material circularity, reducing reliance on high-energy purification routes [77, 89].

Integrating these perspectives also supports technology roadmapping and policy development. Circularity-oriented assessments in adjacent fields, such as the development of closed-loop automotive materials systems, demonstrate how system-level design principles and recovery strategies can reduce resource pressures over time [50, 70]. Semiconductor manufacturing is beginning to adopt similar thinking, particularly in relation to chemical substitution, precursor recovery, modular design, and improved end-of-life management. Circularity frameworks therefore help identify strategic levers such as material substitution toward less critical elements, standardization for disassembly, or the development of recyclability-oriented device architectures that LCA alone would not highlight [90].

Overall, LCA quantifies the environmental cost of existing technologies, while circularity metrics reveal opportunities for retaining material value and mitigating supply risk [91]. Together, they offer a more holistic framework for guiding research, manufacturing innovation, and policy interventions in electronics and optoelectronics, supporting a transition from high-impact linear systems toward more resilient and resource-efficient technology ecosystems.

6. Conclusion

This review contributes three key points to the discussion of sustainability and circularity in electronics and optoelectronics. First, this review shows that the low circularity of III–V semiconductors is mainly determined by device architecture and end-of-life system constraints rather than by the absence of recycling technologies. This conclusion is supported by the material flow analyses and recycling studies discussed in sections 4.2 and 4.3. Second, the review demonstrates that upstream fabrication choices, including material selection, epitaxial growth, and packaging design, strongly influence downstream critical-material dissipation. As discussed in sections 3 and 4.4, many end-of-life losses are effectively determined during manufacturing. Third, evidence synthesized across sections 4 and 5 highlights that III–V semiconductors behave as dissipative critical materials rather than conventionally recyclable metals. This distinction has important implications for both LCA methodology and circular economy policy.

The transition toward sustainable electronics and optoelectronics requires an integrated understanding of how materials, manufacturing processes, and end-of-life pathways collectively shape environmental and resource performance. This review has synthesized evidence across semiconductor material classes ranging from III–V compounds and silicon to germanium and emerging organic systems to demonstrate that sustainability challenges in this sector are fundamentally rooted in material criticality, high-temperature epitaxy, chemical-intensive fabrication, and extremely limited circularity. While advances in device efficiency and miniaturization have driven remarkable technological progress, these improvements alone cannot offset the structurally high embodied impacts embedded into current semiconductor supply chains.

Yet LCA alone cannot capture the broader resource risks that arise from dependency on CRMs with negligible recovery rates. Integrating circularity metrics such as recycled content, end-of-life recovery, and MCIs offers a more holistic understanding of where interventions can meaningfully reduce environmental pressures while improving resource resilience. Together, LCA and circularity frameworks highlight clear strategic priorities: the need to reduce reliance on high-impact III–V materials where feasible, to expand secondary sourcing and closed-loop pathways for germanium and silicon, and to encourage the development of recyclable or low-impact alternatives such as organic electronic materials.

Looking forward, the pathway to a more sustainable and circular semiconductor ecosystem will depend on coordinated action across multiple levels. At the materials level, substituting scarce or high-impact compounds with lower-impact or more recyclable alternatives will be crucial where performance requirements allow. In manufacturing, innovations in low-temperature epitaxy, precursor recovery, green chemistry, and energy-efficient cleanroom operation offer promising routes to reduce environmental intensity. At the product level, design for disassembly, modular architectures, and repairability can enable greater material retention and extend device lifetimes. Finally, systemic interventions such as improved CRM stewardship, dedicated e-waste collection systems for high-value materials, and policy mechanisms that incentivize circularity will be essential to ensure that technological progress aligns with long-term sustainability constraints.

Overall, this review underscores that achieving sustainability in electronics and optoelectronics is not a matter of incremental optimization within existing linear systems, but a structural challenge that requires rethinking how materials are selected, how devices are manufactured, and how value is preserved at end-of-life. By combining LCA with circularity-oriented strategies, the semiconductor industry can move toward a future where high-performance technologies are developed in tandem with environmental responsibility and resource resilience.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Conflict of interest

The authors report there are no competing interests to declare.

Appendix. Glossary of technical terms

1. HVAC—heating, ventilation and Air conditioning. Environmental control system used in semiconductor cleanrooms to maintain extremely tight temperature, humidity and particle specifications. One of the largest energy consumers in a fab.
2. UPW—ultrapure water. Water with resistivity above 18 MΩ·cm, used throughout wafer cleaning and wet processes. UPW generation is highly energy intensive.
3. CMP—chemical mechanical polishing. planarization technique combining mechanical abrasion and chemical etching to flatten metal and dielectric layers. Generates large volumes of slurry waste.
4. Slurry (CMP slurry) Colloidal suspension used in CMP, typically containing SiO_2, CeO_2 or Al_2O_3 nanoparticles along with oxidizers, pH stabilizers and dispersants. Nanoparticle Agglomeration Tendency of nanoparticles in slurry to cluster into larger aggregates due to surface energy effects. A major barrier to slurry recycling.
5. MOCVD—metal–organic chemical vapor deposition high-temperature epitaxy technique widely used for III–V semiconductors such as GaAs, InP and GaN. Relies on highly reactive metal-organic precursors.
6. MBE—molecular beam epitaxy. Ultra-high vacuum epitaxy method enabling atomically controlled III–V growth.
7. PA-MBE—plasma-assisted MBE. MBE variant using plasma to activate nitrogen or other species, enabling lower-temperature growth.
8. ALD—atomic layer deposition. Self-limiting thin-film deposition technique offering sub-nanometer thickness control. Energy intensive due to slow cycle-based processing.
9. SALD—SPATIAL ALD. High-throughput ALD in which precursors are spatially separated rather than temporally sequenced.
10. ALE—atomic layer etching. Self-limiting etching method complementary to ALD, enabling atomic-scale precision in pattern transfer.
11. Photoresist. Polymer material that undergoes photochemical changes during lithography. Typically derived from petrochemicals and dissolved in organic solvents.
12. Petrochemical-Derived Polymers. Polymers synthesized from petroleum-based feedstocks, widely used in conventional photoresists.

13. PGMEA—propylene glycol monomethyl ether acetate. Major solvent in photoresists and edge-bead removal. High volatile organic compound emissions during processing.
14. NMP—N-Methyl-2-pyrrolidone. Powerful polar solvent used for resist stripping; classified as a reproductive toxin.
15. IPA—isopropyl alcohol. Common solvent used in drying and cleaning steps.
16. HF—hydrofluoric acid. Highly corrosive acid used for SiO_2 etching and cleaning; poses severe health risks.
17. H_2SO_4, HCl, NH_4OH. Strong acids and bases used in RCA cleaning and polymer removal.
18. TMGa—trimethylgallium. Metal-organic precursor for Ga epitaxy in MOCVD; pyrophoric and hazardous.
19. TMIn—trimethylindium. Metal-organic precursor for In epitaxy.
20. AsH_3—arsine, PH_3—phosphine. Highly toxic hydrides used as group-V precursors in III–V epitaxy.
21. NF_3—nitrogen Trifluoride, CHF_3—trifluoromethane High-GWP gases used for chamber cleaning and plasma etching.
22. Kerf Loss. Material loss caused by sawing ingots into wafers, particularly significant for brittle materials like GaAs and Ge.
23. Wafer Reclaim. Process of restoring used Si wafers through grinding, polishing and cleaning for reuse.
24. Virgin Substrate. New, unused substrate directly supplied by the manufacturer, as opposed to reclaimed wafers.
25. Circularity (Circular Manufacturing). Ability of a material or process to support closed-loop reuse through recycling, recovery or redesign.
26. TRL—technology readiness level. Metric describing maturity of a technology (TRL 1–3: fundamental research; TRL 4–6: prototype; TRL 7–9: industrial deployment).

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