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Toxicity and energy intensity impacts in the supply chain sustainability of InGaN and InGaP semiconductor technologies

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ABSTRACT

This study presents an ex-ante, geospatially explicit life cycle sustainability assessment of two emerging compound semiconductor technologies, InGaN and InGaP micro-LEDs, across their full supply chains. A total of 80 scenarios (40 per technology) were modelled for 2024, 2030, 2040, and 2050, incorporating geographically distributed fabrication, testing, and use phases and accounting for future energy mix decarbonisation aligned with net-zero targets. Midpoint impacts were assessed for 12 key categories, including toxicity, resource use, and climate-related emissions, while endpoint results focused on human health, ecosystem, and resource impacts. Results indicate that electricity-intensive cleanroom operations initially dominate global warming and marine ecotoxicity impacts; however, under low-carbon electricity pathways, these Scope 2–related contributions decline substantially by mid-century (up to ~ 95%). Consequently, the dominant environmental burden shifts toward Scope 1 impacts from material- and chemical-intensive stages, particularly substrate preparation and epitaxial growth. Toxicity-related impacts remain strongly driven by emissions from chemical precursors and process chemicals in carbon-intensive supply chains, although low-carbon energy pathways reduce overall toxicity by up to ~ 60%. InGaP epitaxial growth contributes a large share of remaining climate and ecotoxicity impacts, whereas InGaN exhibits a more balanced distribution across fabrication phases. Resource depletion impacts also decline markedly (approximately 40–65%), reflecting reduced fossil energy use and lower embodied resource intensity. This integrated framework highlights the interplay of energy sourcing, material use, and chemical management in semiconductor supply chains, providing scenario-specific insights to guide policymakers and industry toward sustainable, low-impact technology deployment.

1. Introduction

1.1. Climate Change, energy transition and the semiconductor sector

Global warming is among the most critical threats to human society. Given that fossil fuel resources are inherently limited, their continued exploitation heightens geopolitical instability and accelerates climate change by driving greenhouse gas (GHG) emissions [1]. Recent studies indicate that GHG emissions are projected to increase by 50%, potentially becoming the leading driver of climate change by 2050 [2]. A key strategy for tackling climate change is the development of a low-carbon economy, which seeks to reduce energy consumption, limit pollution, and lower GHG emissions into the atmosphere [3,4]. As a result, the use of renewable energy and the adoption of more efficient, environmentally friendly technologies are rapidly increasing [5]. In addition, according to the IEA's Net Zero Emissions by 2050 scenario, renewable energy is projected to provide roughly two-thirds of the world's primary energy supply by mid-century [6]. One of the key industries from an environmental perspective is the semiconductor sector, which requires deeper investigation regarding its contribution to environmental pollution. Semiconductor fabrication is a resource-intensive process, characterised by high energy consumption, extensive use of chemicals, and substantial greenhouse gas emissions – particularly fluorinated gases with high global warming potential. In 2020, the industry alone emitted around 64.24 million tons of CO_2-equivalent gases [7].

Geopolitical tensions and trade uncertainties have underscored the importance of securing semiconductor fabrication capabilities. Several

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Nomenclatures

Abbreviation	Full Name
BGA	Ball grid array
DRAM	Dynamic Random-Access Memory
FE	Freshwater Ecotoxicity
FEU	Freshwater Eutrophication
FRS	Fossil Resource Scarcity
GHG	Greenhouse gas
GW	Global Warming
HCT	Human Carcinogenic Toxicity
HNCT	Human Non-Carcinogenic Toxicity
IC	Integrated circuit
IEA	International Energy Agency
InGaN	Indium Gallium Nitride
InGaP	Indium Gallium Phosphide
IR	Ionising Radiation
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
ME	Marine Ecotoxicity
MEU	Marine Eutrophication
MOCVD	Metalorganic Chemical Vapor Deposition
TA	Terrestrial Acidification
TE	Freshwater Ecotoxicity

governments have implemented measures to strengthen the resilience of their semiconductor supply chains [8]. Semiconductor fabricators need to proactively adopt strategies to reduce their Scope 1, 2, and 3 emissions to support the transition to a low-carbon economy. Scope 1 and 2 emissions stems from the company's direct activities and energy use, whereas Scope 3 emissions arise from upstream and downstream value chain processes, including transportation [8].

1.2. Compound semiconductors and Micro-LED technologies

Among the various semiconductor materials, certain compound semiconductors stand out for their superior electronic and optical characteristics, enabling high-performance applications. III–V semiconductors are a class of materials formed by combining group 13 (formerly Group IIIA) elements as cations with group 15 (formerly Group VA) elements as anions. One of the main technological strengths of these materials is their direct bandgap, which enables efficient light absorption and emission. Consequently, they serve as the foundation for nearly all thin-film devices designed for light–matter interaction [9]. Among the many applications of III–V semiconductors, micro-LED displays have emerged as a promising next-generation technology due to their advantages, including low power consumption, fast response time, and high luminous efficiency, which together support the development of highly reliable display systems [10].

In particular, Indium Gallium Nitride (InGaN)-based micro-LEDs have recently attracted significant interest and progress because of their exceptional properties (such as high contrast, strong brightness, broad colour range, and long lifespan) positioning them as promising candidates for next-generation display technologies [11]. Another type is (Indium Gallium Phosphide (InGaP) which features a wide bandgap and exhibits strong operational stability even at elevated temperatures [12]. These factors led to the selection of InGaN and InGaP as representative III–V semiconductors, owing to their complementary optoelectronic properties and widespread use in advanced devices, making them attractive and promising for conducting a sustainability assessment. Assessing the sustainability of InGaN and InGaP is crucial because these materials are widely used in high-performance optoelectronic devices which are key to next-generation display and energy technologies. Understanding their environmental impacts can help identify strategies to reduce resource consumption, energy use, and waste generation. This knowledge is essential for developing more sustainable semiconductor supply chains and supporting the transition to low-carbon, energy-efficient technologies.

1.3. Research gaps and study contributions

Building on these insights, this study presents a comparative, geospatially explicit sustainability assessment of two promising compound semiconductor technologies, InGaN and InGaP micro-LEDs, which compete for part of the display and lighting market. Despite their technological importance, the existing literature provides only limited insights into their environmental performance. To address this gap, we developed a comprehensive supply chain system boundary extending from raw material extraction – including critical minerals – through to the point of use. The modelling and analysis combine both primary and secondary datasets, ensuring robustness and data completeness.

A novel contribution of this work lies in conducting an ex-ante life cycle assessment (LCA) aligned with global net-zero targets, considering future energy transition pathways across different countries involved in the designed supply chains. Our supply chain models incorporate realistic international configurations, with geographically distributed stages that capture the inherent complexity of semiconductor production. This approach provides results that are directly relevant to decision-makers, policymakers, and industry stakeholders. To systematically evaluate potential futures, we designed 40 scenarios for each technology (80 in total) across four timeframes (2024, 2030, 2040, and 2050), informed by International Energy Agency (IEA) country-level energy mix projections. This enables a forward-looking assessment of the ecological performance of these emerging semiconductor technologies under diverse and evolving supply chain conditions.

To the best of our knowledge, no previous study has combined geospatially explicit modelling, critical mineral considerations, predictive LCA, and international supply chain scenario analysis in a single, integrated framework. While prior LCAs of semiconductors have largely focused on single technologies, static supply chains, or limited geographic scopes, our work uniquely integrates dynamic, geographically distributed supply chains with future energy scenarios, providing actionable insights for sustainable semiconductor deployment.

1.4. Advances in semiconductor sustainability

This section reviews the current state of the art in semiconductor sustainability, with a focus on LCA, supply chain impacts, and emerging challenges in compound semiconductor technologies. Many studies have assessed different types of semiconductors to improve performance, enhance efficiency, and promote their functional potential [13–17]. These studies have primarily focused on enhancing various aspects of the technology; however, the carbon footprint and overall sustainability of this promising technology have not been explored to the same extent as its technological performance. Relatively few studies have examined life cycle assessments, circular economy approaches, or the broader supply chain impacts, creating a significant knowledge gap regarding the environmental and resource-related consequences of widespread semiconductor deployment. Filling these gaps is crucial to ensure that improvements in performance are not achieved at the cost of ecological integrity and sustainability.

Several studies have examined the environmental impacts of semiconductor technologies using LCA, consistently highlighting energy-intensive fabrication, chemical use, and substrate preparation as primary contributors to environmental burdens across both conventional and emerging semiconductor applications [18–26]. These findings underscore the importance of process optimisation, energy efficiency, and careful material management to reduce environmental impacts.

A recurring theme across the literature is that upstream material production and chemical-intensive fabrication steps dominate the life cycle impacts of semiconductor technologies. For instance, analyses of GaAs and GaInP/GaAs solar modules, DRAM, and NAND-flash memory consistently identify epitaxial growth, wafer fabrication, and the use of process chemicals as the main drivers of environmental burdens [18–22,25,27–31]. Similarly, emerging technologies such as carbon nanotube-enabled devices, printed electronics, and III–V precursors show that material synthesis and purification can be highly energy- and resource-intensive, contributing substantially to overall environmental impacts [27,28,30–32]. Life cycle assessments of emerging display technologies, including OLEDs and Micro-LEDs, further confirm that manufacturing stages dominate overall environmental impacts, despite efficiency gains during device operation [33–36]. These observations suggest that improvements in operational efficiency alone are insufficient for achieving meaningful reductions in environmental impacts; attention to upstream material sourcing, fabrication efficiency, and process design is essential.

Downstream processes, including packaging, testing, and module assembly, also contribute to environmental impacts, particularly in integrated circuit packaging and ball grid array systems [37–39]. While these contributions are generally smaller than those of upstream fabrication, they are nonetheless significant when evaluating full cradle-to-gate footprints, highlighting the importance of considering the complete product system in environmental assessments.

Several studies have also highlighted methodological limitations in previous semiconductor LCA work. Common gaps include the use of static energy mixes, limited geospatial specificity, and the lack of semiconductor-specific sustainability indicators, which reduce the comparability and applicability of results [19–23,26,31,32,40]. Some work addresses these limitations by developing frameworks for environmental profiling and tailored indicators, demonstrating the value of scenario analysis and process-specific metrics to better guide industry practices and policy decisions [21,40]. Moreover, emerging technologies such as printed electronics, carbon nanotube devices, OLEDs, and Micro-LEDs illustrate the need to consider trade-offs between novel material impacts and process-level efficiencies, further emphasising the importance of incorporating both upstream and downstream considerations [27,30,32–36].

Finally, the literature consistently demonstrates that technology transitions in the semiconductor industry do not automatically result in environmental improvements. Studies comparing CRT, LCD, and LED monitors, as well as emerging GaAs/Si nanowire solar cells, show that as devices become more energy-efficient during operation, the relative and absolute importance of manufacturing processes increases [18–26,37]. For complex III–V devices, including Micro-LEDs, upstream processes such as epitaxy, photolithography, and chemical-intensive fabrication dominate environmental impacts, often outweighing use-phase benefits. These insights directly support the rationale for the present study, which focuses on InGaN and InGaP Micro-LED technologies, highlighting the significance of upstream material and fabrication stages as environmental hotspots and identifying where process improvements and supply chain optimisation can yield the greatest environmental benefits [33–36].

Table 1 summarises the key methodological differences between prior semiconductor and Micro-LED LCA studies and the present work, highlighting how this study advances existing approaches through geospatially explicit, forward-looking, and internationally integrated supply chain modelling.

Table 1
Comparison of methodological scope between prior semiconductor and Micro-LED LCA studies and the present work.

Aspect	Typical prior semiconductor & display LCAs	This study
Technology focus	Single semiconductor or display technology	Comparative assessment of InGaN and InGaP Micro-LED technologies
Life cycle perspective	Mostly cradle-to-gate or partial system boundaries	Comprehensive supply chain from raw material extraction (including critical minerals) to point of use
Supply chain configuration	Simplified or nationally aggregated supply chains	Realistic, international, multi-country supply chain configurations
Geographical resolution	Limited or non-explicit geographic representation	Fully geospatially explicit modelling across supply chain stages
Energy system representation	Static or present-day electricity mixes	Dynamic, country-specific future energy scenarios aligned with net-zero pathways
Temporal perspective	Retrospective or present-day assessment	Ex-ante assessment across multiple future timeframes (2024–2050)
Scenario analysis	Limited or absent	Systematic scenario design covering multiple supply chain and energy transition futures
Critical material considerations	Often excluded or treated implicitly	Explicit inclusion of critical minerals in supply chain modelling
Decision relevance	Primarily academic or technology-specific	Direct relevance for policy, industry, and long-term sustainability planning

2. Methodology and modelling approach

2.1. Life cycle assessment

LCA is a systematic approach used to quantify and evaluate material and energy flows, along with the resulting environmental impacts, associated with products and services throughout their entire life cycle [41–43]. LCAs are widely used to support decision-making in transformative strategies, including the decarbonisation of energy systems, the implementation of circular economy approaches, and the advancement of sustainable consumption across various energy and environmental contexts. LCA can be a powerful tool for informed decision-making, enabling systematic tracking of a wide range of environmental impacts across the entire product development value chain [44,45]. Its application helps identify and address critical sustainability challenges essential for future development and growth [46]. The LCA is carried out following ISO 14040, which comprises four main steps: (I) goal and scope definition, (II) life cycle inventory (LCI) analysis, (III) life cycle impact assessment (LCIA), and (IV) results interpretation [47–52]. These steps are displayed in Fig. 1.

2.2. Goal and Scope definition

In this initial stage of the LCA study, the focus is on addressing what, how, and why of the analysis. This phase defines the system boundaries and establishes the functional unit (FU) [53]. A crucial component of any life cycle assessment is the FU, as it serves as the reference point against which all other data in the assessment are standardised [54].

The primary goal of this study is to evaluate and compare the environmental sustainability of InGaN and InGaP micro-LED semiconductor fabrication across different international supply chain configurations. By quantifying life cycle impacts at both midpoint and endpoint levels, this study aims to identify critical environmental hotspots, resource dependencies, and regional differences in semiconductor fabrication. The results will provide insights into the potential benefits of alternative

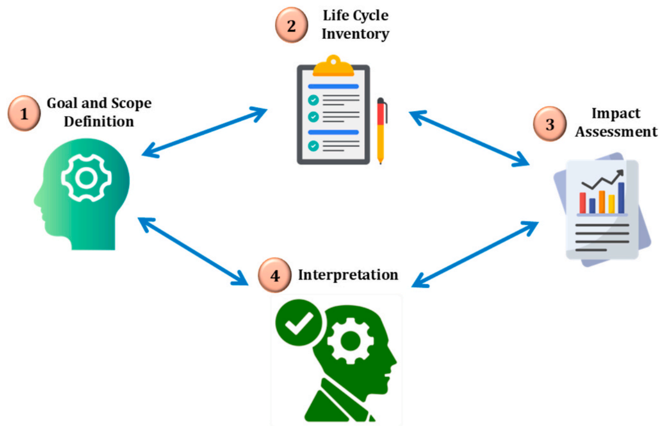

Fig. 1. Four main steps of LCA approach.

supply chain strategies, technological improvements, and circular economy pathways, thereby supporting decision-making for industry stakeholders, policymakers, and researchers seeking to reduce the environmental footprint of compound semiconductor production. OpenLCA version 2.4.1 was selected as the software tool for conducting the analysis. The selected FU is 1 cm2 of processed wafer, making it suitable for a comparative study between the two mentioned systems. The functional unit precisely defines the product's size and type, specifying the quantitative function it provides, which serves as the basis for the life cycle analysis [55]. The functional unit for this study is 1 cm^2 of processed wafer, including all upstream and fabrication processes. This unit was selected because it provides a consistent basis for comparing environmental impacts between InGaN and InGaP micro-LEDs, irrespective of wafer size or device layout. One square centimetre represents a standard portion of wafer that can be diced into multiple micro-LED dies, allowing normalisation of impacts by yield. Differences in substrate materials, epitaxial stack thickness, and process chemistry between InGaN and InGaP are explicitly captured in the material and energy inventories, ensuring that impacts per cm^2 remain directly comparable across the two technologies. This approach allows meaningful assessment of the relative environmental performance while maintaining functional relevance to device production.

Mass transfer processes, which are unique to micro-LED assembly, were included implicitly within the Testing & Packaging phase of the system boundary. Due to the use of aggregated industrial datasets and confidentiality constraints, energy and material inputs associated with die transfer, inspection, bonding, and packaging were not disaggregated into individual sub-steps. Instead, these operations were represented as a combined downstream fabrication stage consistent with available industrial information. While mass transfer is recognised as an energy- and yield-critical step in micro-LED production, its environmental contribution is captured at an aggregated level in this study.

In addition, the uncertainty assessment is conducted using a Monte Carlo simulation approach, enabling the propagation of input data variability through the life cycle model to evaluate the robustness of the results.

2.3. Life cycle inventory (LCI)

The development of a LCI involves identifying and quantifying the material and energy flows exchanged between the product system and its surrounding environment [56]. A comprehensive and reproducible inventory for the construction and operation phases of the analysed power plants is developed using a combination of primary and secondary data. Primary data are obtained from real industry information and engineering expertise; however, due to confidentiality constraints, they cannot be disclosed in this study. Any missing information is supplemented with secondary sources, including literature and publicly available databases such as Ecoinvent v3.9. Cleanroom energy was modelled as a single aggregated value per functional unit due to limitations in available data. The total value includes all HVAC, process tool, and baseload power consumption.

2.4. Life cycle impact assessment (LCIA)

The LCIA phase evaluates the potential environmental impacts associated with the elementary flows identified in the LCI. This process generally includes the following steps: (I) defining impact categories, (II) classifying inventory data into these categories, (III) characterising their contributions, (IV) normalising the results, (V) grouping related impacts, and (VI) applying weighting to indicate their relative significance [57].

The ReCiPe 2016 Midpoint (H) and endpoint methods were applied for the environmental impact assessment. ReCiPe 2016 was selected due to its comprehensive and widely accepted framework for LCIA. It integrates both midpoint (problem-oriented) and endpoint (damage-oriented) approaches within a consistent methodology. This dual structure enables detailed identification of environmental hotspots at the midpoint level, while also translating results into broader areas of protection, including human health, ecosystem quality, and resource scarcity at the endpoint level. ReCiPe 2016 provides updated characterisation factors and a broader set of impact categories, making it particularly suitable for complex systems such as semiconductor supply chains with multiple environmental mechanisms.

Normalisation was applied using the global (World) reference region provided in ReCiPe 2016, expressing results relative to annual per-capita global environmental burdens. No weighting was applied in the main analysis to avoid introducing value-based preferences into the comparison of scenarios. It also facilitates the visualisation of results by enabling the plotting of radar diagrams based on log-scaled values, allowing for clearer comparison across various impact categories. For radar plot visualisation, normalised midpoint results were transformed using a base-10 logarithmic scaling to improve readability across impact categories with different orders of magnitude. The transformed values were then linearly rescaled to a 0–1 range for visual comparison. Impact categories with very small, normalised values approaching zero were assigned a value of zero after scaling. These transformations were applied consistently across all scenarios and technologies.

2.5. Uncertainty analysis

Uncertainty in the life cycle inventory arises from both primary industrial data and secondary database sources. For secondary data, uncertainty is inherently incorporated through the underlying database models. For primary data, where detailed statistical information was not available due to confidentiality constraints, uncertainty ranges were assigned based on data quality considerations, including measurement reliability, technological representativeness, and temporal relevance.

Uncertainty ranges were assigned based on data quality considerations and typical variability reported in LCA practice. Lower variability was assumed for baseline (2024) conditions with higher data reliability, while higher variability was applied to estimated parameters and future projections (2050), reflecting increased uncertainty associated with technological evolution and energy system transitions.

2.6. Results interpretation

The final stage of the LCA process involves compiling, analysing, and interpreting the results obtained from both the LCI and LCIA. This phase provides a comprehensive basis for drawing meaningful conclusions, formulating recommendations, and guiding decision-making in alignment with the study's defined goals and scope. Moreover, insights gained during this stage may highlight data gaps, methodological limitations, or opportunities for improvement −potentially leading to further iterations of the assessment and revisions to the initial objectives or system boundaries [58].

3. Supply chain scenarios development

The supply chain scenarios for InGaN and InGaP semiconductors were developed to represent realistic global configurations of raw material sourcing, wafer fabrication, device testing and packaging, and final use. These scenarios capture both existing and emerging supply chain structures, allowing assessment of environmental performance, logistical complexity, and regional dependency. The analysis integrates different transportation modes between each stage (primarily lorry, sea freight, and air freight) to account for trade-related impacts within a LCA framework. Ten distinct scenarios were created for each semiconductor, ranging from regionally concentrated supply chains to fully globalised pathways, with the aim of comparing environmental and strategic trade-offs under varying production geographies.

For InGaN, gallium and indium are the main critical raw materials, while InGaP production requires gallium, indium, and phosphorus, which are among the most critical materials for compound semiconductor fabrication. These elements are considered critical due to their limited global supply, high geopolitical concentration, and strategic importance in enabling advanced optoelectronic technologies such as light-emitting diodes (LEDs), high-efficiency solar cells, and high-speed electronic devices. The selected countries reflect realistic global producers and processors of these critical elements. Critical material sourcing locations were selected based on current global production and refining dominance, reflecting established industrial supply chains rather than speculative future reconfiguration. Country assignments for key materials and chemical precursors were informed by publicly available statistics on global production shares and refining capacity (e.g., United States Geological Survey (USGS) [59] and IEA reports [60]). Within each scenario, material sourcing locations were held constant across all timeframes (2024–2050), while only electricity carbon intensities were varied according to projected grid decarbonisation pathways. This approach isolates the influence of energy system transitions on environmental impacts and avoids confounding effects from simultaneous changes in material sourcing assumptions.

China serves as a major global supplier of gallium and indium, given its dominance in refining and mineral processing. South Korea and Russia represent secondary suppliers with advanced refining capacity and growing semiconductor industries. Canada contributes to indium recovery as a by-product of zinc ore processing, while Morocco is included for its global leadership in phosphate rock production, a key precursor to phosphorus. These selections ensure that the raw material sourcing stage reflects the actual geographical distribution of primary resource extraction and refining activities.

The fabrication stage involves countries that are established semiconductor manufacturing hubs, including China, Taiwan, Japan, South Korea, the United States, and the United Kingdom. Taiwan and South Korea host advanced foundries, which lead in epitaxial growth and device fabrication. Japan and the United States are included due to their technological maturity and extensive research and development activities in compound semiconductor technologies. The United Kingdom is incorporated as an important supplier of epitaxial growth and to represent European manufacturing potential and the integration of cleaner energy sources in semiconductor production. This combination of Asian, North American, and European fabrication centres allows for analysis of both regional and transcontinental supply structures.

Testing and packaging are modelled in countries where back-end semiconductor operations are well established. China and Malaysia represent global centres for large-scale packaging and assembly due to their cost competitiveness and specialised labour. Taiwan is included for its advanced packaging technologies and proximity to major foundries. The United States and Germany are added to represent high-end quality control and integration stages typical of final assembly for export-oriented semiconductor devices. The use phase involves countries such as the United Kingdom, Japan, Germany, the United States, China, and Taiwan, which are among the world's largest semiconductor-consuming markets.

In several scenarios, certain stages are divided between two countries, indicated as 50%–50%. This denotes that half of the total production volume or process share is assumed to occur in one country and the other half in another. The 50%–50% split also allows assessment of how regional variations in electricity decarbonisation influence environmental impacts across the supply chain. This split reflects the growing trend of multi-sourcing and distributed fabrication in the semiconductor industry, which enhances supply chain resilience, reduces geopolitical risk, and allows companies to optimise costs and carbon footprints across regions. This approach captures the reality of parallel production systems, where different facilities contribute to the same global output. A summary of defined supply chain scenarios is brought in Table 1.

Overall, these ten scenarios for both InGaN and InGaP enable systematic evaluation of how geographical distribution, transportation mode, and multi-country fabrication affect the environmental footprint, economic efficiency, and resilience of compound semiconductor supply chains. The approach integrates both conventional and emerging global production patterns, making it possible to compare localised, regional, and fully globalised supply chains. Furthermore, the incorporation of shared production and flexible scenario logic ensures the framework can adapt to future semiconductor market developments and circular economy strategies. This scenario design thus provides a robust foundation for subsequent life cycle modelling, hotspot identification, and sustainability optimisation in compound semiconductor fabrication systems. Fig. 2 illustrates the supply chain diagram of assessed technologies. As shown in Table 2, the production of InGaN and InGaP micro-LEDs is distributed across multiple countries with transport between these stages contributing to the overall environmental impacts assessed in the LCA.

For each technology (InGaN and InGaP), 10 base supply chain scenarios were defined to represent different geographic distributions of fabrication, testing, and use phases. Each base scenario was combined with four timeframes (2024, 2030, 2040, 2050), resulting in 40 scenarios per technology and 80 scenarios in total. Over the timeframes, only electricity mixes are varied according to projected decarbonisation pathways. Process-level inputs, including chemical and material usage per functional unit, are kept constant, allowing direct comparison of the effect of decarbonisation on environmental impacts.

Country-specific electricity carbon intensities (g CO_2/kWh) were used to model Scope 2 impacts in the supply chains. Observed 2024 values were taken from Our World in Data (UK and Taiwan) and the IEA Electricity 2025 report (China and USA). Projections for 2030, 2040, and 2050 were based on the IEA Net Zero Emissions (NZE) scenario, reflecting increasing renewable energy penetration and grid decarbonisation. China's 2050 intensity is higher than other countries, consistent with its official net-zero target in 2060. The 2040 values were interpolated linearly between 2030 and 2050. These carbon intensities were applied to electricity consumption in all process stages to calculate electricity-related emissions per functional unit (1 cm2). A table of all values is provided in the Supplementary Material.

International transportation between supply chain stages was modelled using a combination of lorry (road), sea freight, and air freight. Road transport was assumed for intra-country movements between facilities and ports, while sea freight was used as the default mode for intercontinental bulk material transport. Air freight was applied only for high-value, low-mass semiconductor components where rapid delivery is typical in industry practice. Assumed transport distances were estimated based on representative trade routes between selected producing and processing countries within each supply chain scenario. Mode shares were determined according to material characteristics and

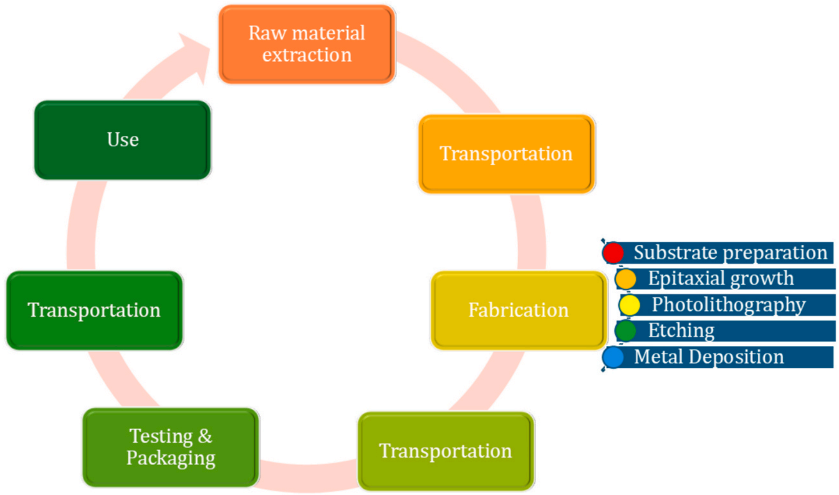

Fig. 2. Supply chain diagram and system boundary.

Table 2
Summary of designed supply chain scenarios for both InGaN and InGaP.

Scenario name	Semiconductor Type	Critical Raw Material Source	Fabrication Location	Testing & Packaging Location	Final Use Region
S.N.1	InGaN	China (Gallium, Indium)	Taiwan	Taiwan	UK
S.N.2	InGaN	China (Gallium, Indium)	China	China	China
S.N.3	InGaN	China (Gallium), South Korea (Indium)	UK	Malaysia	Japan
S.N.4	InGaN	China (Gallium), Canada (Indium)	USA	USA	USA
S.N.5	InGaN	China (Gallium), South Korea (Indium)	South Korea	China	Germany
S.N.6	InGaN	Russia (Gallium), China (Indium)	Taiwan (50%) / South Korea (50%)	Malaysia	China
S.N.7	InGaN	Russia (Gallium), South Korea (Indium)	China (50%) / Japan (50%)	Taiwan	USA
S.N.8	InGaN	China (Gallium), Canada (Indium)	UK (50%) / USA (50%)	UK	Germany
S.N.9	InGaN	China (Gallium, Indium)	USA (50%) / China (50%)	China	Taiwan
S.N.10	InGaN	China (Gallium), South Korea (Indium)	Japan (50%) / Taiwan (50%)	Taiwan	UK
S.P.1	InGaP	China (Gallium, Indium), Morocco (Phosphide)	Taiwan	Taiwan	UK
S.P.2	InGaP	China (Gallium, Indium), Morocco (Phosphide)	China	China	China
S.P.3	InGaP	China (Gallium), South Korea (Indium), China (Phosphide)	UK	Malaysia	Japan
S.P.4	InGaP	China (Gallium), Canada (Indium), China (Phosphide)	USA	USA	USA
S.P.5	InGaP	China (Gallium), South Korea (Indium), Morocco (Phosphide)	South Korea	China	Germany
S.P.6	InGaP	Russia (Gallium), China (Indium), Morocco (Phosphide)	Taiwan (50%) / South Korea (50%)	Malaysia	China
S.P.7	InGaP	Russia (Gallium), South Korea (Indium), China (Phosphide)	China (50%) / Japan (50%)	Taiwan	USA
S.P.8	InGaP	China (Gallium), Canada (Indium), China (Phosphide)	UK (50%) / USA (50%)	UK	Germany
S.P.9	InGaP	China (Gallium, Indium), Morocco (Phosphide)	USA (50%) / China (50%)	China	Taiwan
S.P.10	InGaP	China (Gallium), South Korea (Indium), Morocco (Phosphide)	Japan (50%) / Taiwan (50%)	Taiwan	UK

industry logistics norms, with air freight representing a minor fraction of total transported mass.

Fig. 3 provides a simplified layer-by-layer representation of the fabrication sequence for the two device types considered in this study. The structures are shown in a generic form, clearly illustrating the substrate materials and epitaxial layer stacks. For the GaInP-based devices, the diagram explicitly shows epitaxial growth on a GaAs substrate, which is the conventional choice for micro-LEDs due to lattice matching and established performance characteristics. In contrast, the InGaN-based devices are illustrated on a Sapphire substrate, one of the common industrial substrates for InGaN with known improvements in operating efficiency compared to silicon.

4. Results and Discussion

The results obtained from the modelled systems are presented for both midpoint and endpoint impact assessment methods. For the midpoint results, 12 key impact categories were selected, representing the most significant and influential environmental impacts. Other categories with negligible contributions, based on normalised results, were excluded from this study. A cut-off rule was applied: any midpoint category whose normalised contribution was below 1% of total impacts across all scenarios and years was omitted. This ensures that only categories with meaningful influence on the results were retained. A complete list of excluded categories and their normalised contributions is provided in the Supplementary Information Table S2. The selected midpoint categories focus primarily on toxicity and energy-related impacts, which are the main objectives of this research. Regarding the

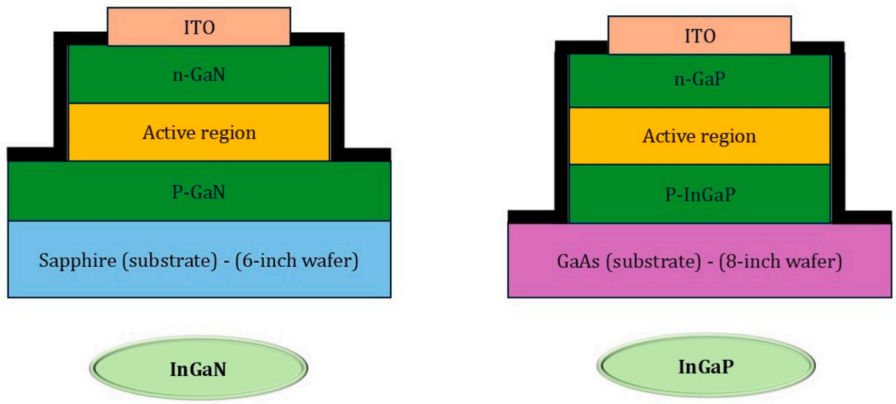

Fig. 3. Layer-by-layer schematic diagram of the epitaxial growth structures used for InGaN- and GaInP-based semiconductor devices.

endpoint results, three main impact categories are presented: human health, resources, and ecosystems.

4.1. Midpoint results – Impact categories

The environmental performance of InGaN and InGaP across multiple supply chain configurations (2024–2050) reflects the interplay of energy sourcing, chemical management, and regional resource characteristics. The impacts are assessed from process-driven hotspots, regional sensitivities, and long-term decarbonisation effects views, highlighting differences between the two semiconductor technologies. Fig. 4 presents heatmaps based on midpoint results, illustrating the spatial and temporal variations across all assessed impact categories for InGaN and InGaP semiconductors in 2024, 2030, 2040, and 2050. These heatmap plots provide a visual comparison of environmental impact results across different supply chain scenarios (y-axis) and time horizons (x-axis). Each cell in the heatmap corresponds to the impact value of a specific scenario in a given year, with the numerical result overlaid for clarity. The background colour of each cell is scaled according to the magnitude of the value, where warmer colours (yellow–red) indicate higher impacts and cooler colours (green–blue) indicate lower impacts.

4.1.1. Fossil resource scarcity (FRS)

Fig. 4a and 4b show the FRS impact values and their trends from 2024 to 2050 across all supply chain scenarios, following the net-zero plan. In Scenario S.N.1 (Taiwan fabrication and testing, UK use), InGaN's FRS decreases from 426.6 to 107.7 g oil eq/cm^2 (≈74% reduction), while InGaP in S.P.1 declines from 418.94 to 114.46 g oil eq/cm^2 (≈73%). Fabrication in coal-intensive regions (China: S.N.2, S.P.2) results in higher resource use, whereas low-carbon regions achieve lower FRS. Mixed-location scenarios (e.g., S.N.6: Taiwan–South Korea) show intermediate results. By 2050, InGaP FRS is higher because GaAs substrates and Phosphine and Arsine chemistry keep fossil-linked demand significant, even under decarbonised grids.

4.1.2. Freshwater ecotoxicity (FE)

Fig. 4c and 4d illustrate the FE impact values and variations from 2024 to 2050 across all supply chain scenarios. In Scenario S.N.1, InGaN FE declines from 23.68 to 9.42 g 1,4-DCB eq/cm^2 (≈63% reduction), while InGaP decreases from 32.04 to 18.42 g (≈44%). High-emission regions (China: S.N.2, S.P.2) maintain higher FE, whereas low-carbon regions with greener energy mixes (UK, USA: S.N.3, S.N.8) achieve lower impacts.

4.1.3. Freshwater eutrophication (FEU)

Fig. 4e and 4f display the FEU impact values and variations from 2024 to 2050. In Scenario S.N.1, InGaN FEU falls from 5.44×10^{-1} to 8.90×10^{-2} g P eq/cm^2 (≈84% reduction), while InGaP drops from 5.86×10^{-1} to 1.51×10^{-1} g P eq/cm^2 (≈74%). The FEU impact mainly arises from metal-organic precursors, phosphine, ammonia, and process wastewater generated during substrate preparation and chemical handling.

4.1.4. Global warming (GW)

Fig. 4g and 4 h show the GW impact for each supply chain scenario, illustrating the changes from 2024 to 2050 according to the net-zero plan. GW potential declines steadily across scenarios from 2024 to 2050 following net-zero targets in different countries. Scenario S.N.1 shows InGaN decreasing from 1771.52 to 424.6 g CO_2 eq/cm^2 (≈76% reduction), with InGaP following a similar trend. Coal-heavy grids (China: S.N.2, S.P.2) have the highest impacts in 2024 (>2,000 g CO_2 eq/cm^2), whereas low-carbon regions (UK: S.N.3/S.P.3; UK–USA: S.N.8/S.P.8) achieve the lowest. By 2050, emissions converge in both systems (∼420–580 g CO_2 eq/cm^2 for InGaN; ∼460–610 g CO_2 eq/cm^2 for InGaP).

4.1.5. Human carcinogenic toxicity (HCT) and Non-Carcinogenic toxicity (HNCT)

Fig. 4i and 4j show the results for HCT, while Fig. 3k and 3 l illustrate the corresponding results for HNCT. These impacts reflect human health risks from chemical emissions, particularly the use of acids (e.g., hydrochloric, nitric, and phosphoric acids) during substrate cleaning, etching, and chemical synthesis steps. Scenario S.N.1 shows InGaN HCT dropping from 53.91 to 23.88 g 1,4-DCB eq/cm^2 (≈56% reduction) and InGaP from 55.5 to 26.82 g (≈52%). HNCT follows similar trends with higher absolute values. High-emission, fossil fuel-dependent regions (China) maintain elevated toxicity, while regions with greener electricity grids (UK and USA) reduce impacts. Mixed-location scenarios produce intermediate outcomes, reflecting the combined effect of process location and chemical handling practices.

4.1.6. Ionising radiation (IR)

Fig. 4m and 4n present the IR impact values for both technologies over the considered period. IR impacts decline steadily across all scenarios from 2024 to 2050, with InGaN dropping from about 35.15 to 29.01 g U-235 eq/cm^2 (≈15–18% reduction) and InGaP from 39.22 to 33.27 g (≈15–16%). Despite InGaN generally being more energy-intensive, InGaP consistently shows higher IR values, which can be attributed to its reliance on resource- and mining-intensive materials such as gallium, arsenic and phosphorus.

4.1.7. Marine ecotoxicity (ME)

Fig. 4o and 4p display the ME impact values for each supply chain and their changes over the 26-year period. ME reflects the potential harm of chemical releases to aquatic ecosystems, driven by both process chemicals and energy-related emissions. In Scenario S.N.1, InGaN's ME

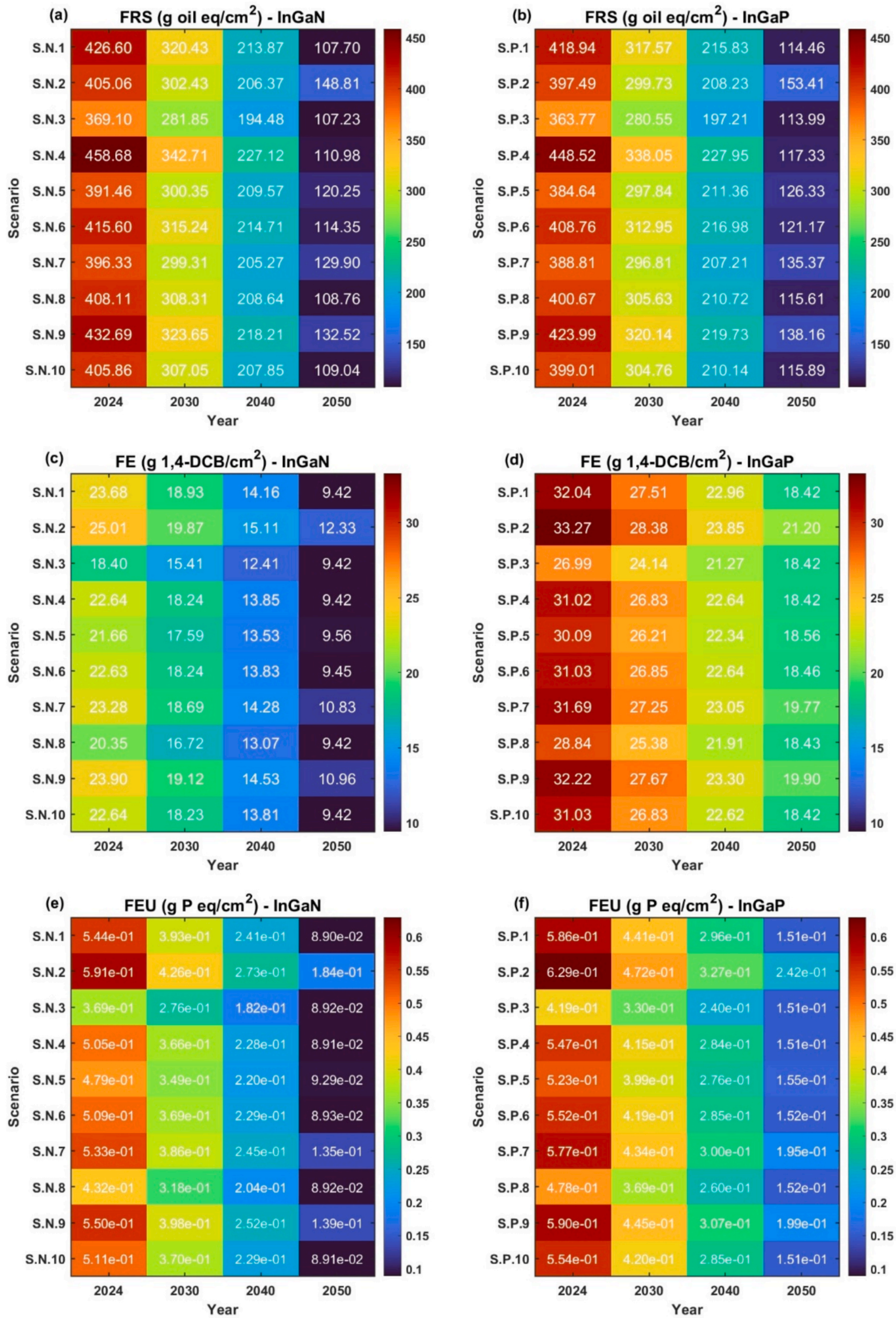

Fig. 4. Heatmaps of scenario-based environmental impacts for InGaN and InGaP semiconductors across the years 2024, 2030, 2040, and 2050.

impact decreases from 33.12 to 13.27 g 1,4-DCB eq/cm^2 (≈61% reduction), while InGaP declines from 47.05 to 28.1 g (≈40%). Differences between InGaN and InGaP largely stem from substrate materials and the use of hazardous precursors, with InGaP exhibiting

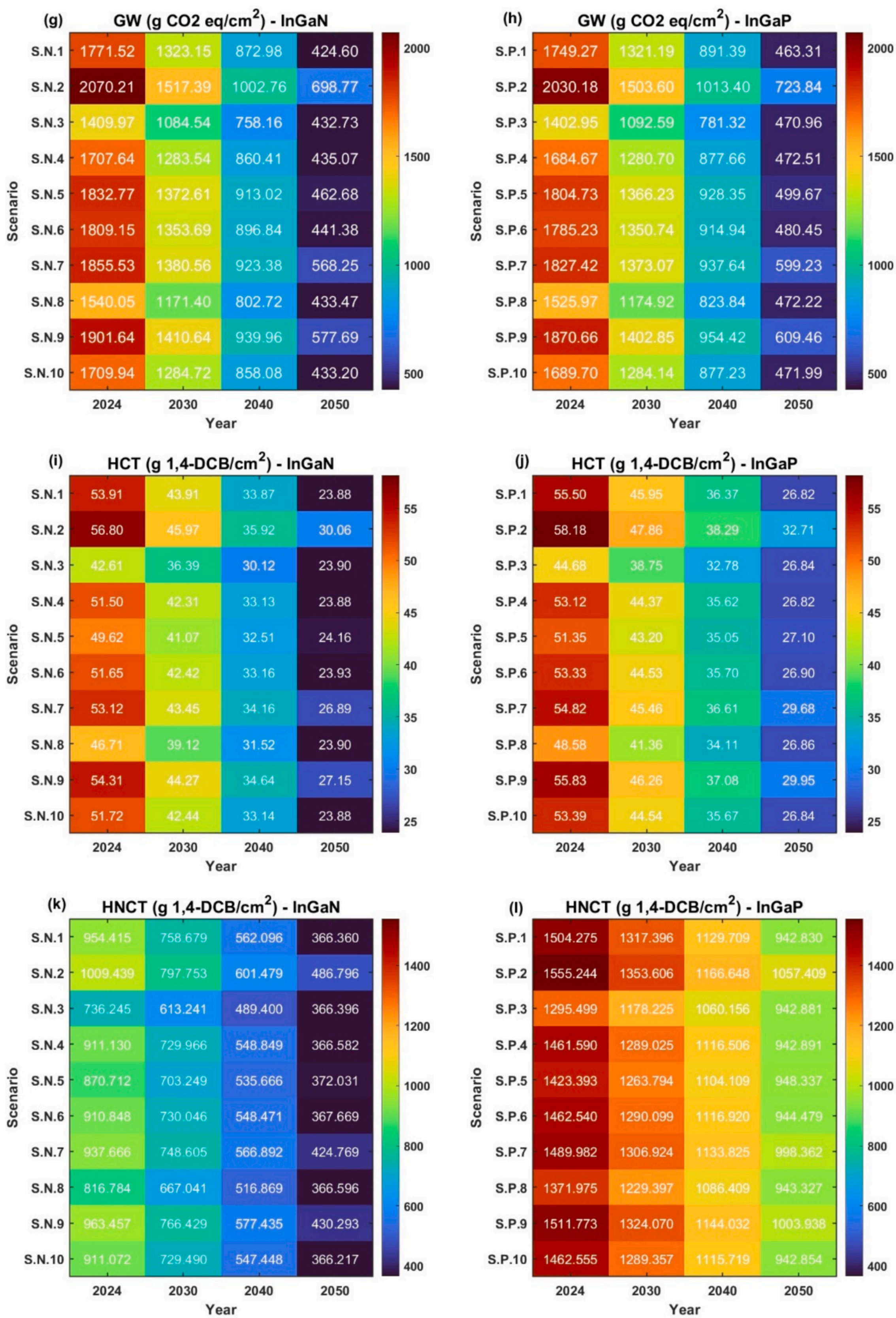

Fig. 4. (*continued*).

higher toxicity due to its more chemically intensive processes.

4.1.8. Marine eutrophication (MEU)

Fig. 4q and 4r illustrate the MEU impact values across the different supply chains and how they evolve over the 26-year period. Scenario S.

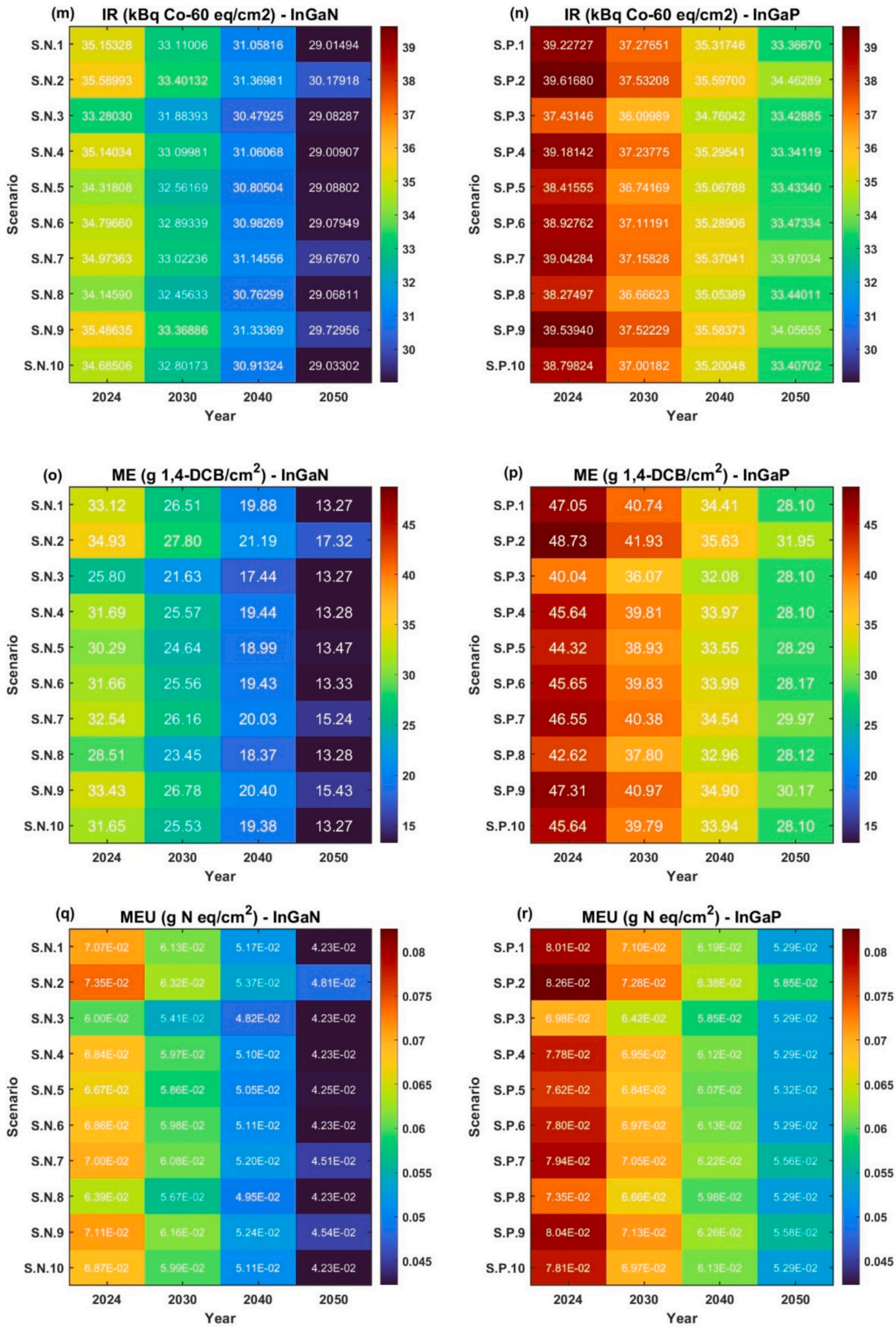

Fig. 4. (*continued*).

N.1 shows InGaN decreasing from 7.07×10^{-2} g to 4.23×10^{-2} g N eq/cm^2 (≈40% reduction) and InGaP from 8.01×10^{-2} g to 5.29×10^{-2} g (≈34%). InGaP exhibits higher MEU due to greater chemical usage during its more pollutant material usage, highlighting the importance of waste management and process optimisation in mitigating chemical release to marine environments.

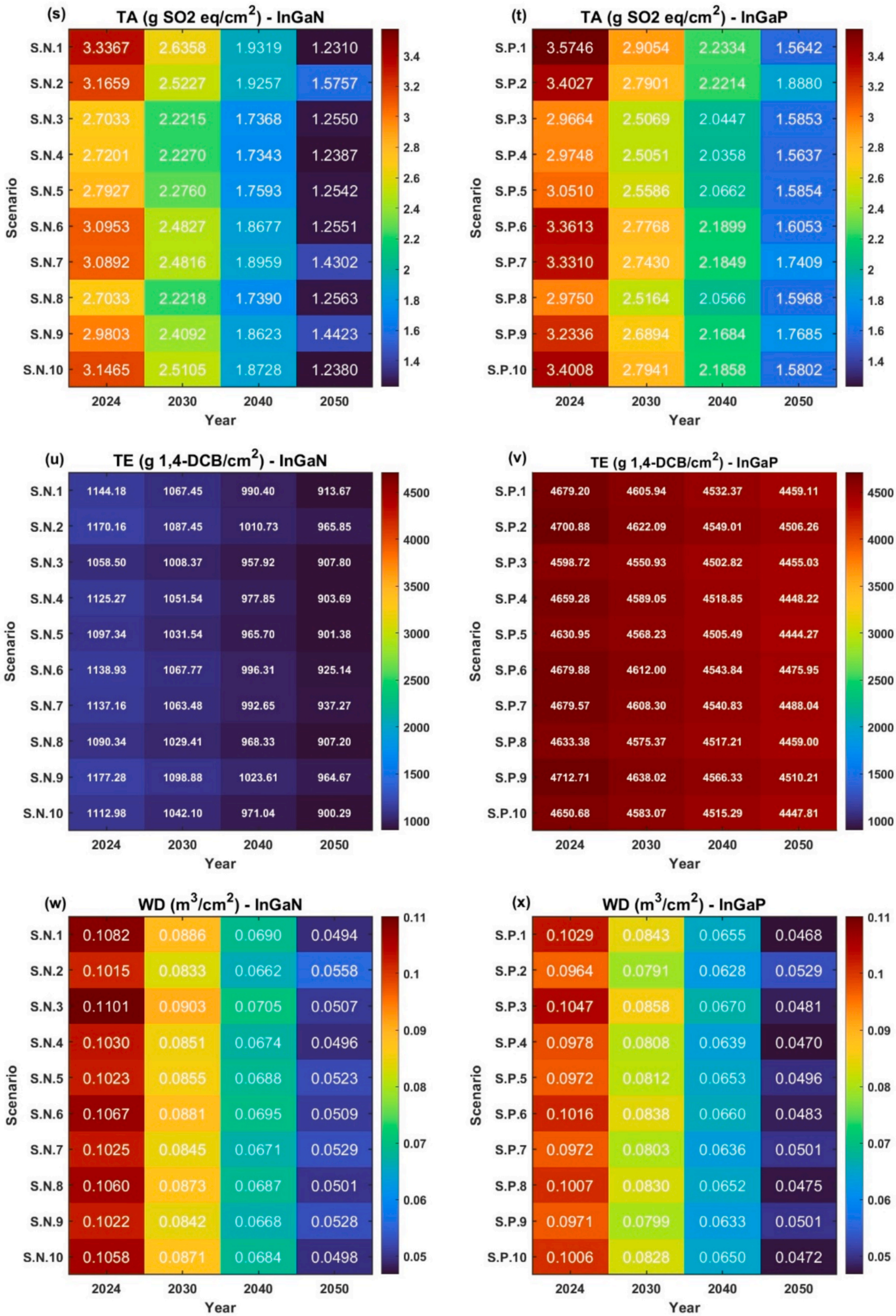

Fig. 4. (*continued*).

4.1.9. *Terrestrial acidification (TA)*

Fig. 4s and 4 t depict the decreasing trend of TA impact values across all defined supply chains up to 2050. TA reflects emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3). Scenario S.N.1 sees InGaN decreasing from 3.34 to 1.23 g SO_2 eq/cm^2 (≈63% reduction), and InGaP from 3.57 to 1.56 g (≈56%) from 2024 to 2050.

These emissions mainly arise from energy-intensive fabrication steps, metal–organic precursor decomposition (e.g., TMGa, TMIn), and chemical processing, demonstrating the need for cleaner energy and controlled precursor usage to reduce acidifying pressures.

4.1.10. Terrestrial ecotoxicity (TE)

Fig. 4u and 4v show the TE impact values and their trends from 2024 to 2050 across all supply chain schemes. TE quantifies the potential harm to freshwater organisms caused by chemical releases during semiconductor fabrication. In Scenario S.N.1, InGaN decreases from 1144.18 to 913.67 g 1,4-DCB eq/cm^2 (≈20% reduction), while InGaP declines from 4679.2 to 4459.11 g 1,4-DCB eq/cm^2 (≈5%) between 2024 and 2050. InGaP consistently shows higher TE due to more chemically intensive fabrication processes.

4.1.11. Water depletion (WD)

The variations in WD impact for both technologies across all scenarios up to 2050 are shown in Fig. 4w and 4x. WD quantifies freshwater consumption for substrates, cleaning, chemicals, and cooling. Scenario S.N.1 shows InGaN decreasing from 0.108 to 0.049 m^3 water eq/cm^2 (≈55% reduction) and InGaP from 0.103 to 0.047 (≈54%). Water scarcity and inefficient treatment in Taiwan and China elevate impacts, while water-abundant regions with recycling infrastructure (UK, USA, and Malaysia) mitigate them. InGaN's sapphire substrates drive higher water use than InGaP's gallium arsenide.

4.1.12. Integrated insights

Across all categories, energy-intensive fabrication drives both FRS and GW; chemical precursors influence toxicity and ecotoxicity; and water management determines WD outcomes. Strategic combinations of low-carbon fabrication, optimised testing, and careful chemical and water management can reduce environmental burdens by 40–85% depending on scenario and technology, highlighting the benefits of sustainable supply chain planning for InGaN and InGaP semiconductors.

The attribution of impacts to sapphire substrate processing and to heavy metal precursors and solvents can be directly traced to explicit life cycle inventory flows and their associated emission pathways. Sapphire substrates contribute primarily through upstream energy-intensive processes such as crystal growth, wafer slicing, polishing, and cleaning, which are reflected in high electricity demand per functional unit. These energy-related inventory flows dominate climate change, particulate matter formation, and human health-related impact categories via electricity-related emissions to air.

Impacts associated with heavy metal precursors and solvents used in epitaxial growth, deposition, and wet processing steps are linked to inventory flows of metal-containing chemicals and organic solvents. In the LCIA, these inputs contribute mainly to human carcinogenic toxicity, human non-carcinogenic toxicity, freshwater ecotoxicity, and marine ecotoxicity categories. The dominant contributions arise from ReCiPe 2016 characterisation factors associated with metal emissions to water and soil and solvent-related emissions to air, as represented in the background datasets. This linkage clarifies the cause–effect relationships between process-level material inputs, emission pathways, and toxicity-related impact results.

These results demonstrate that the ecological impacts of InGaN and InGaP semiconductors are fundamentally supply chain–dependent, reflecting interactions among energy sources, chemical use, process intensity, and regional resource availability. Strategic supply chain design is essential to minimise environmental pressures while maintaining technological performance.

4.2. Midpoint results – Phase contributions

4.2.1. Overarching trend

The phase contributions for the first scenario for both InGaN and InGaP (S.N.1 and S.P.1) are presented here, as the differences in contributions across other scenarios are small, avoiding repetition of similar results. Fig. 5 shows the contribution of each phase to GW and ME impacts for scenario S.N.1. Results showed the shift from energy-dominated cleanroom impacts to material/process-dominated impacts. Cleanroom contributions fall sharply in both GW and ME by 2050 (75 and 93%), suggesting either decarbonisation of the electricity/energy used by cleanrooms in the scenario or efficiency/technology changes that lower their relative impact. As cleanroom impacts decline, the relative importance of material-intensive and chemical-use phases (substrate, epitaxy, photolithography, metal deposition, testing & packaging) rises. Although treated as a monolithic block, typical cleanroom energy use is dominated by HVAC and cooling systems, followed by process tools. Targeting these components for efficiency improvements is expected to provide the largest reductions in energy-related environmental impacts.

4.2.2. Phase contributions to GW

- o Early dominance of cleanroom energy (≈38% in 2024) declines to ≈9% in 2050. This pattern is consistent with strong decarbonisation (e.g., cleaner electricity grid or lower energy intensity in cleanrooms).
- o Substrate preparation and epitaxial growth become the major GW contributors by 2050 (substrate preparation ≈28.9%, epitaxial growth ≈23.2%). This indicates that upstream bulk crystal growth and wafer processing for substrates, together with energy- and precursor-intensive epitaxial growth processes, are significant and growing contributors to total impacts. The use of sapphire substrates (Al_2O_3), which require high-temperature synthesis and polishing, leads to substantial embodied energy and CO_2 emissions, explaining their strong contribution to GW.
- o Photolithography shows a large proportional growth (from 5.6% to 14.8%), not due to an absolute increase in impact, but rather because the energy-related burdens of other phases decline under energy mix decarbonisation by 2050. As a result, the remaining impacts in photolithography become increasingly dominated by chemical and material applications (notably photoresists, solvents, and etchants) that retain ecotoxic and GHG-related potentials despite overall system-level decarbonisation.

4.2.3. Phase contributions to ME

- o Testing & packaging and photolithography appear to grow substantially in relative terms, with testing & packaging becoming the largest contributor to ME by 2050 (22.8%). This does not necessarily indicate higher absolute impacts but rather reflects that decarbonisation and energy efficiency improvements reduce the dominance of cleanroom-related burdens, thereby amplifying the relative visibility of material- and chemical-related ecotoxicity. In these stages, persistent use of packaging polymers, adhesives, glues, coatings, and photolithography chemicals with high freshwater and marine toxic potentials continues to drive the ME category, as these substances are less affected by energy mix decarbonisation or process electrification.
- o Cleanroom ME impact drops dramatically (26.4% to 1.9%), again suggesting that changes that reduce energy-related impacts do not necessarily reduce toxic releases or that cleanroom toxic burdens are mitigated in the scenario.
- o Substrate, metal deposition, and photolithography are also notable contributors to ME by 2050 (substrate 23.1%, photolithography 16.1%, metal deposition 12.3%), reinforcing the view that material production and process chemicals drive ecotoxicity. The sapphire substrate contributes to ME impacts due to alumina residues and chemical polishing agents (e.g., acids, bases, and slurry compounds) used during wafer preparation. Additionally, the use of heavy metal precursors in metal deposition (e.g., Ni, Au) and solvent-based

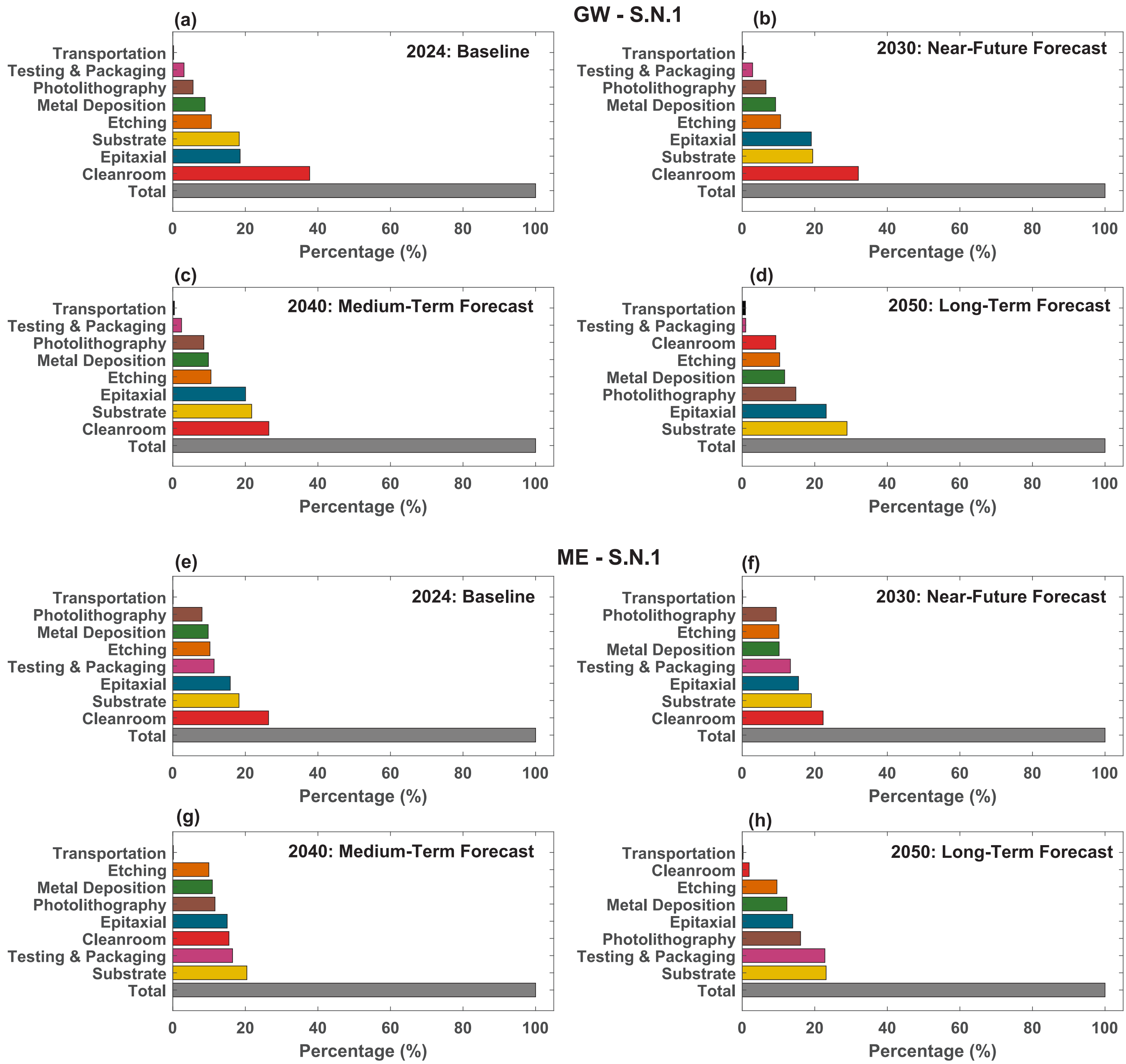

Fig. 5. Horizontal bar charts showing the relative contribution (%) of GW and ME impact categories of different semiconductor fabrication processes for scenario S.N.1 in the years 2024, 2030, 2040, and 2050.

photolithography chemicals enhances ecotoxicity potential through wastewater emissions and residual contamination.

For GW impacts, Fig. 5 shows the relative contribution (%) of each fabrication phase, while Table 3 provides the corresponding absolute

Table 3
Phase-wise impact values for GW potential of the InGaN (S.N.1) and InGaP (S.P.1) compound semiconductor supply chains across 2024, 2030, 2040, and 2050.

Phase	Unit	S.N.1 2024	N.P.1	S.N.1 2030	N.P.1	S.N.1 2040	N.P.1	S.N.1 2050	N.P.1
Cleanroom	g CO_2-eq/cm^2	639.90	615.22	423.84	423.57	231.07	231.05	39.33	39.34
Epitaxial	g CO_2-eq/cm^2	325.39	393.59	252.01	323.43	175.08	252.80	98.27	182.59
Substrate	g CO_2-eq/cm^2	320.95	290.73	257.20	229.23	189.73	167.58	122.67	106.10
Etching	g CO_2-eq/cm^2	178.92	169.50	140.05	125.51	91.81	81.47	43.86	37.57
Metal Deposition	g CO_2-eq/cm^2	152.39	136.97	121.63	103.98	85.65	70.95	49.68	38.04
Photolithography	g CO_2-eq/cm^2	95.32	83.44	86.60	72.53	74.76	61.51	62.78	50.50
Testing & Packaging	g CO_2-eq/cm^2	54.75	54.75	37.98	37.92	21.04	21.04	4.12	5.05
Transportation	g CO_2-eq/cm^2	3.90	5.07	3.84	5.02	3.84	4.99	3.89	4.12
Total GW	g CO_2-eq/cm^2	1771.52	1749.27	1323.15	1321.19	872.98	891.39	424.60	463.31

GW values for all supply chain phase under scenarios S.N.1 and S.P.1. This allows readers to distinguish between apparent relative increases due to decarbonisation of other phases and actual changes in absolute GW impacts over time.

4.2.4. Overarching patterns

Fig. 6 shows the contribution of each phase to GW and ME impacts for scenario S.P.1. The InGaP supply chain exhibits a pronounced shift in environmental burden from energy-intensive cleanroom operations toward epitaxial growth and substrate preparation. This mirrors the pattern observed for InGaN but with much greater concentration of impact in the epitaxial growth.

4.2.5. Phase contributions to GW

- The epitaxial growth process becomes the dominant source of GHG emissions, rising from 22.5% in 2024 to 39.4% in 2050. This increase suggests that, despite energy decarbonisation, epitaxial growth remains highly energy- and material-intensive due to high-temperature operations, long process durations, and precursor gas use (e.g., trimethylgallium, phosphine). The decomposition of these precursors releases CO_2 and other by-products such as phosphine (PH_3), which, although used in closed systems, contributes indirectly to GW through energy-intensive synthesis.
- Substrate preparation follows as the second-largest contributor, accounting for 22.9% in 2050, reflecting the high embodied energy and resource intensity of substrate materials such as gallium arsenide (GaAs) wafers. GaAs crystal growth and wafer processing require

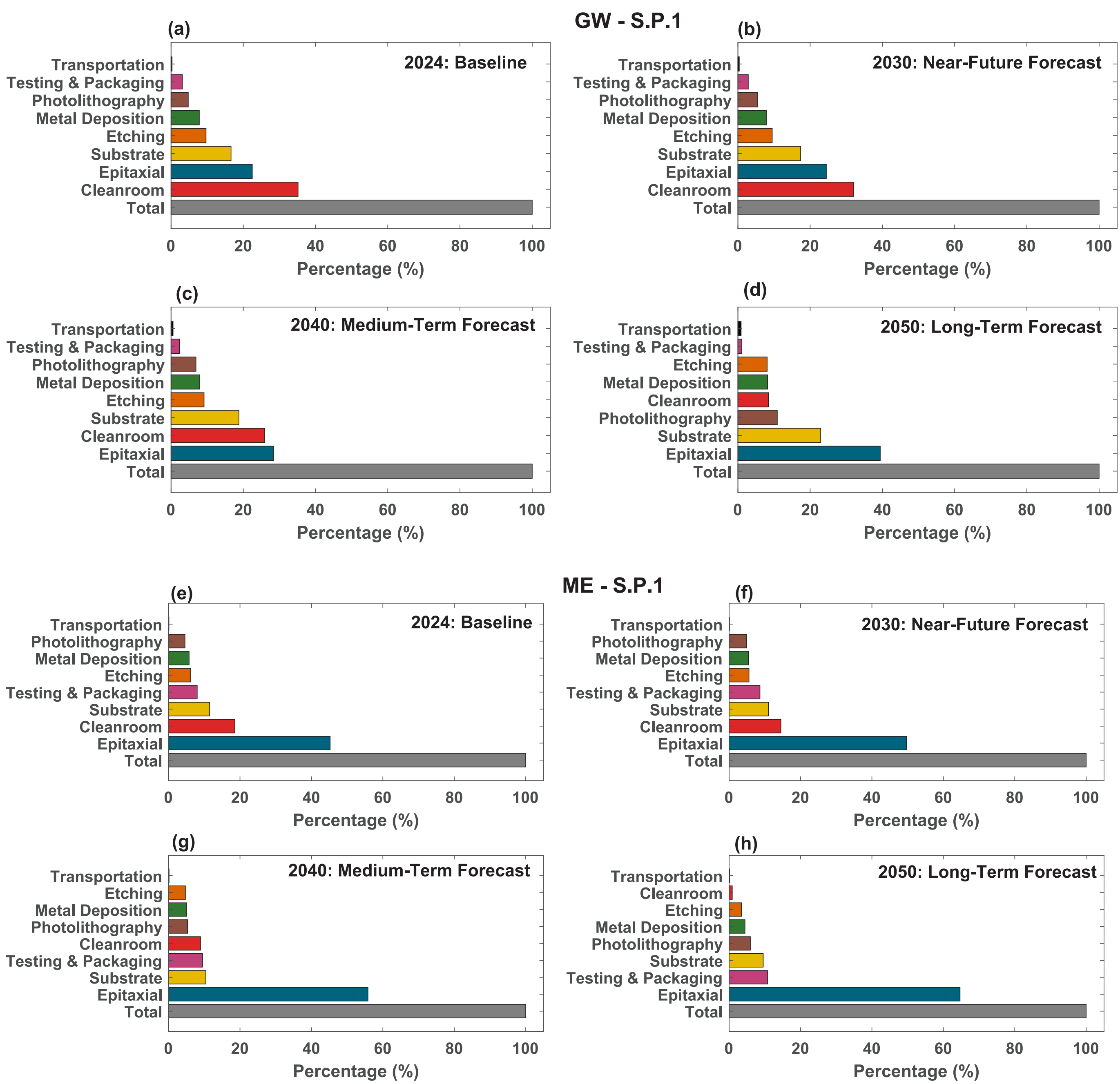

Fig. 6. Horizontal bar charts showing the relative contribution (%) of GW and ME impact categories of different semiconductor fabrication processes for scenario S.P.1 in the years 2024, 2030, 2040, and 2050.

arsenic handling and multiple thermal cycles, both of which elevate the carbon footprint.

o Photolithography also increases notably (from 4.8% to 10.9%), not because of a rise in absolute impacts but as a result of the shift from energy-intensive to material-intensive contributions under the decarbonised energy mix of 2050.

o As cleanroom and process energy burdens decline, the relative influence of chemical and material use (including acids (HCl, H_2SO_4), solvents, and etchants) becomes more pronounced in patterning and etching steps.

4.2.6. *Phase contributions to ME*

o For ME, the epitaxial growth dominates throughout the period, increasing from 45.3% in 2024 to 64.7% in 2050. This reflects the chemical-intensive nature of epitaxial growth – particularly the use of metalorganic precursors, acids, and phosphorus compounds that have high ecotoxicity potentials. The toxicity is amplified by the potential release or treatment of arsenic-containing effluents from GaAs substrates and phosphine-derived by-products.

o Cleanroom impacts decline sharply (−95.2%), primarily because cleanrooms are highly energy-intensive, and the transition to greener electricity supplied by the national grid network significantly reduces their contribution. The toxic material-related impacts of cleanroom operations remain relatively low compared to other phases.

o Testing & packaging and photolithography show moderate increases (reaching 10.8% and 6.0% by 2050, respectively), suggesting persistent contributions from chemical residues, adhesives, and coatings used in these phases.

o Etching and metal deposition impacts gradually decrease, implying improved solvent recovery and process containment.

4.2.7. *Comparative insight: InGaP vs. InGaN*

A comparative assessment of InGaN and InGaP under Scenario S.N.1 reveals distinct patterns in environmental impact distribution across supply chain phases. InGaP demonstrates a clear epitaxial growth dominance, with the epitaxial growth contributing over 60% to ME and around 40% to GW by 2050, whereas InGaN presents a more balanced impact profile distributed among epitaxial growth, substrate preparation, and photolithography. Both materials exhibit a pronounced decline in cleanroom-related contributions for both impact categories, reflecting progressive decarbonisation of the electricity supplied by the grid network by 2050.

However, material composition plays a crucial differentiating role. InGaP fabrication relies on GaAs substrates and phosphorus-based precursors, introducing arsenic- and phosphine-related ecotoxicity risks and higher embodied carbon from crystal growth. In contrast, InGaN employs sapphire substrates, which, while energy-intensive to produce, avoid heavy-metal toxicity but still contribute substantially to GW due to high-temperature oxidation and polishing requirements. Additionally, InGaN's photolithography phase gains importance through chemical-intensive patterning, whereas InGaP's epitaxial layer dominates due to long growth cycles and complex precursor chemistry.

Overall, these contrasts highlight the material-specific environmental sensitivities inherent to compound semiconductor fabrication and emphasise the need for tailored mitigation strategies that address both substrate-related energy burdens and precursor-related toxicity potentials unique to each system.

A sensitivity assessment was performed to evaluate the effect of air freight share on transportation impacts. Although increasing the air freight proportion can sharply raise the transportation-related environmental impacts, the overall contribution of transportation remains very low compared to critical phases such as fabrication, substrate preparation, and chemical-intensive processes. All data are normalised based on the functional unit of 1 cm^2 of processed wafer. Consequently, variations in transport mode and distance result in negligible changes (<1%) to both midpoint and endpoint impact categories, confirming that transportation does not significantly influence the overall environmental results.

Similarly, for ME, Fig. 6 presents the relative contributions (%) of each phase, and Table 4 reports the absolute ME values.

4.3. *Midpoint results – Normalised Log-Scaled*

Fig. 7 presents the radar diagram of normalised results (log-scaled 0–1) for 2024 and 2050. Applying the log scale provides a clearer comparison across impact categories by capturing relative differences and enhancing overall comparability. This approach prevents categories with very large values from dominating the visualisation, while allowing smaller categories to remain visible. It therefore captures relative differences more effectively and highlights shifts in the dominance of specific impact categories between 2024 and 2050. As an example of evaluating log-scaled results, the outcomes for the S.N.1 and S.P.1 scenarios are presented here, while results for other scenarios show similar patterns with only minor differences in values.

For InGaN (2024), marine ecotoxicity (ME, 1.0) is the dominant contributor, followed by human carcinogenic toxicity (HCT, 0.955), freshwater ecotoxicity (FE, 0.951), and human non-carcinogenic toxicity (HNCT, 0.876). Other categories such as terrestrial ecotoxicity (TE, 0.767), freshwater eutrophication (FEU, 0.74), and fossil resource scarcity (FRS, 0.669) also show significant relative contributions. Categories with the lowest relative impacts include ionising radiation (IR, 0.532) and water depletion (WD, 0.662). Overall, the toxicity- and ecotoxicity-related categories are clearly the environmental hotspots for InGaN.

In InGaN (2050), the log-scaled values indicate reductions across most categories. Marine ecotoxicity (ME, 0.905) and human carcinogenic toxicity (HCT, 0.859) remain dominant, but their relative magnitudes are lower than in 2024. Freshwater ecotoxicity (FE, 0.838) and human non-carcinogenic toxicity (HNCT, 0.803) also remain important, suggesting that improvements over time may mitigate overall burdens, but ecotoxicity remains the key concern.

For InGaP (2024), the pattern is like InGaN, with marine ecotoxicity (ME, 1.0), freshwater ecotoxicity (FE, 0.956), and human carcinogenic toxicity (HCT, 0.942) as the leading categories. Human non-carcinogenic toxicity (HNCT, 0.884), terrestrial ecotoxicity (TE, 0.831), and fossil resource scarcity (FRS, 0.668) also contribute substantially. These results reinforce that toxicity and ecotoxicity impacts dominate the environmental profile of InGaP in 2024.

By 2050, InGaP shows a reduction across most categories. Marine ecotoxicity (ME, 0.944), freshwater ecotoxicity (FE, 0.919), and human carcinogenic toxicity (HCT, 0.872) continue to dominate, while categories like fossil resource scarcity (FRS, 0.585) and global warming (GW, 0.519) have comparatively lower relative impacts. The overall trend indicates a shift toward improved environmental performance in the future scenario, though toxicity-related categories remain the major environmental hotspots.

In summary, focusing on these 12 impact categories demonstrates that for both InGaN and InGaP, toxicity (human and ecotoxicity) and marine/freshwater ecotoxicity categories consistently dominate, while resource scarcity, global warming, and eutrophication play secondary roles. The log-scaled radar plots effectively highlight these differences and show clear reductions in most categories by 2050, reflecting potential benefits from technological improvements and supply chain transitions.

To complement the normalised log-scaled radar plots, Table 5 reports absolute midpoint results in their original units for the representative scenarios S.N.1 and S.P.1 as illustrative examples, enabling interpretation of absolute impact magnitudes alongside relative hotspot comparisons.

Table 4
Phase-wise impact values for ME potential of the InGaN (S.N.1) and InGaP (S.P.1) compound semiconductor supply chains across 2024, 2030, 2040, and 2050.

Phase	Unit	S.N.1 2024	S.P.1	S.N.1 2030	S.P.1	S.N.1 2040	S.P.1	S.N.1 2050	S.P.1
Cleanroom	g 1,4-DCB eq/cm^2	8.74	8.74	5.91	5.91	3.08	3.08	0.25	0.25
Epitaxial	g 1,4-DCB eq/cm^2	5.25	21.29	4.11	20.26	2.98	19.21	1.85	18.18
Substrate	g 1,4-DCB eq/cm^2	6.04	5.41	5.05	4.50	4.06	3.60	3.07	2.69
Etching	g 1,4-DCB eq/cm^2	3.39	2.92	2.69	2.27	1.98	1.62	1.27	0.98
Metal Deposition	g 1,4-DCB eq/cm^2	3.23	2.71	2.70	2.23	2.17	1.74	1.64	1.25
Photolithography	g 1,4-DCB eq/cm^2	2.67	2.16	2.49	2.00	2.31	1.84	2.14	1.67
Testing & Packaging	g 1,4-DCB eq/cm^2	3.77	3.77	3.53	3.52	3.27	3.27	3.02	3.03
Transportation	g 1,4-DCB eq/cm^2	0.03	0.05	0.03	0.05	0.03	0.05	0.03	0.05
Total ME	**g 1,4-DCB eq/cm^2**	**33.12**	**47.05**	**26.51**	**40.74**	**19.88**	**34.41**	**13.27**	**28.10**

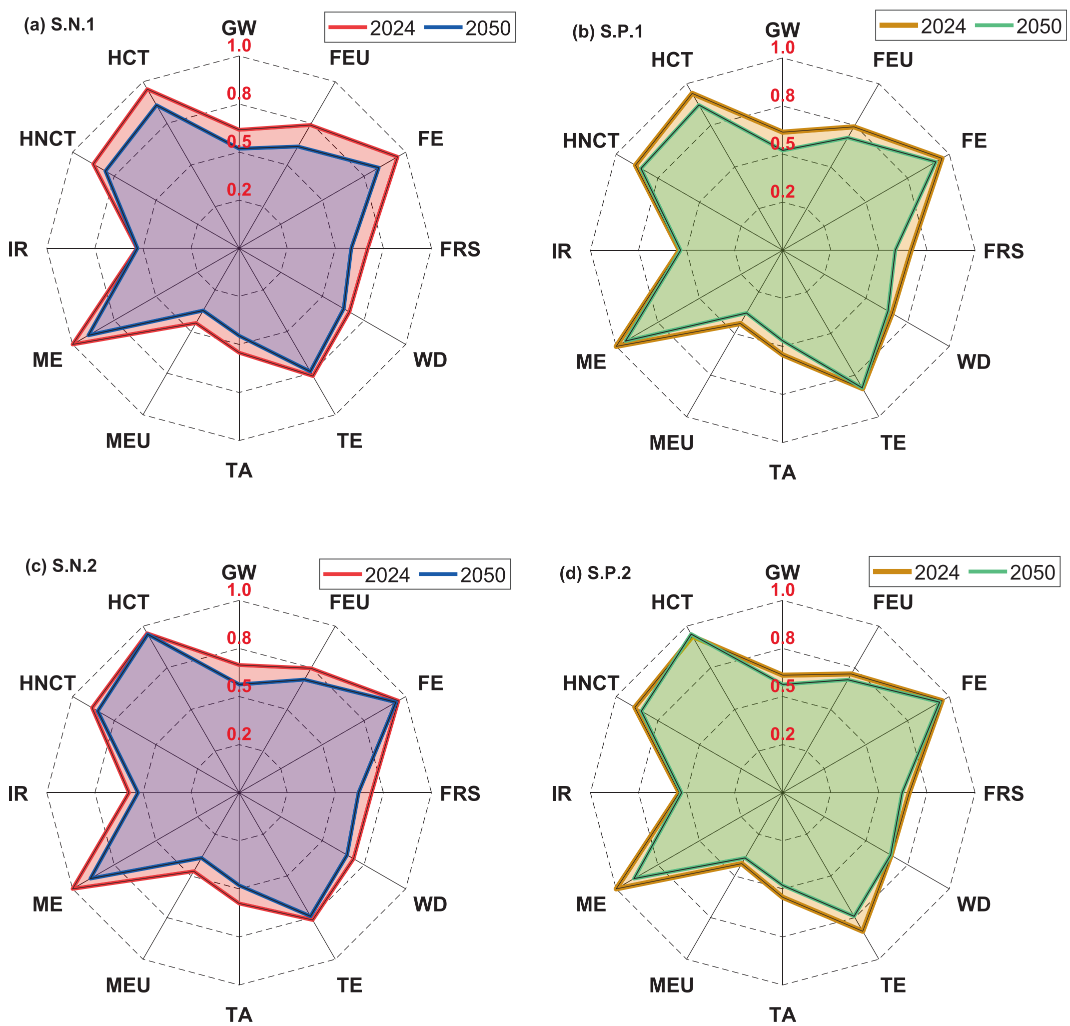

Fig. 7. Radar plots of normalised (log-scaled) environmental impact scores across different impact categories for the years 2024 and 2050.

4.4. *Endpoint results*

4.4.1. *Endpoint results – Human health (HH)*

The Human Health impacts of InGaN and InGaP semiconductors, expressed in DALY/cm^2, reflect cumulative potential effects of environmental emissions on population health, integrating multiple midpoints impacts into a single endpoint metric. Unlike midpoint categories, which quantify specific environmental burdens, the endpoint assessment translates these impacts into estimated health damage, providing a direct measure of societal consequences. Fig. 8a and 8b illustrate decreasing trend in HH impacts from 2024 to 2050 across all InGaN and InGaP supply chain scenarios, reflecting the benefits of energy mix decarbonisation and reduced emission intensities over time.

4.4.1.1. General Trends. Across all supply chain scenarios, HH impacts for both InGaN and InGaP demonstrate a consistent decline from 2024 to 2050, in line with anticipated decarbonisation, net zero target, and relevant stricter pollution controls. For InGaN, impacts decrease from $2.41–3.23 \times 10^{-6}$ DALY/cm^2 in 2024 to $8.65 \times 10^{-7}–1.21 \times 10^{-6}$ DALY/cm^2 in 2050, whereas InGaP exhibits slightly higher absolute values ($2.61–3.37 \times 10^{-6}$ DALY/cm^2 in 2024 to $1.11–1.55 \times 10^{-6}$ DALY/cm^2 in 2050), suggesting marginally greater health risks linked to its

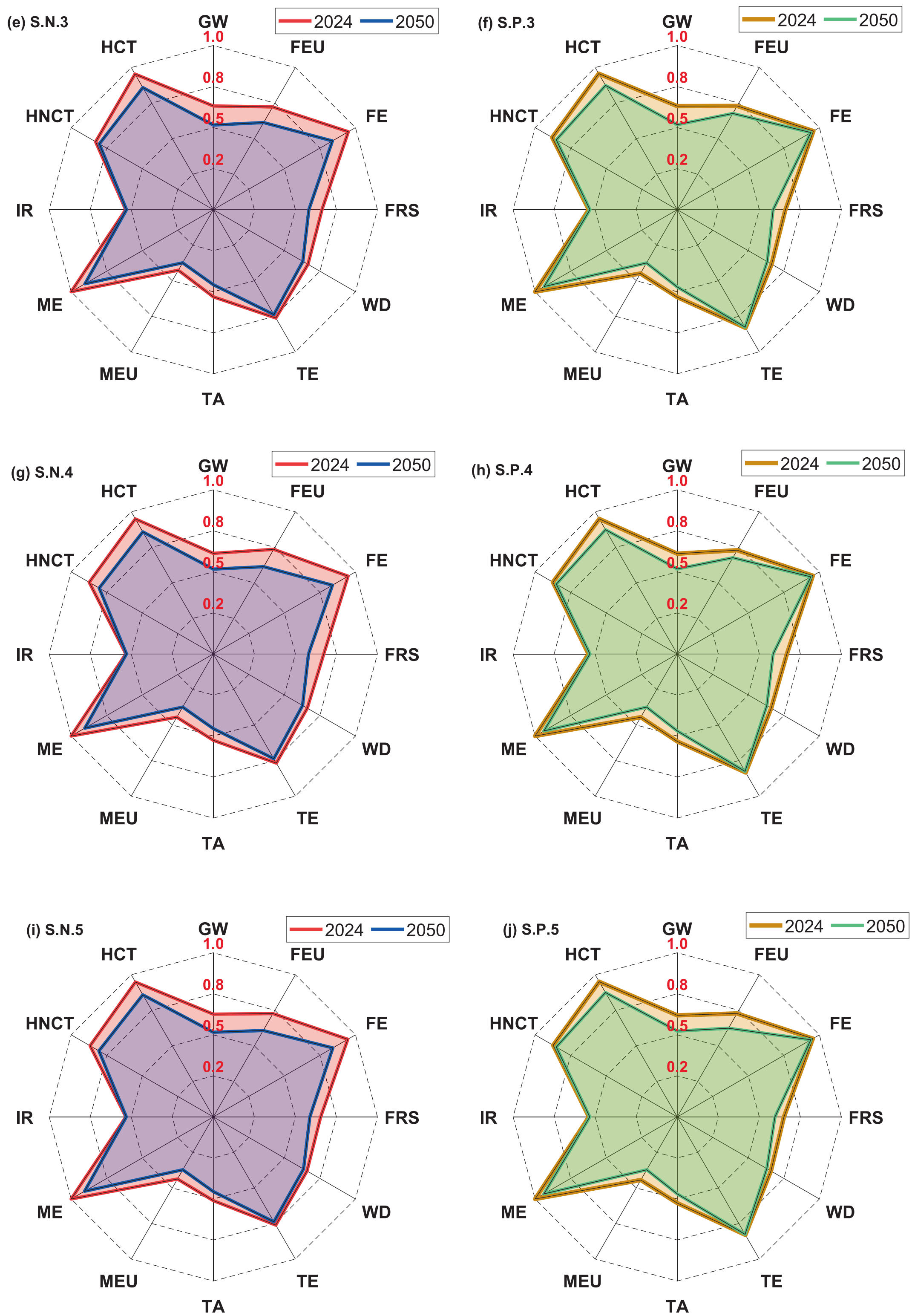

Fig. 7. (*continued*).

fabrication and material use.

4.4.1.2. Scenario-Specific Observations. Energy-intensive scenarios: Semiconductor fabrication occurs mainly in regions heavily dependent on coal, oil, and gas, with limited renewable energy, circularity, or green fabrication. Examples include S.N.2 and S.P.2, which show the highest HH damage due to elevated emissions and climate-related stressors. Mixed-fabrication scenarios with partial involvement of carbon-intensive countries (e.g., S.N.7, S.P.7) also exhibit above-average HH impacts, highlighting the influence of regional energy and emission profiles.

Low-carbon scenarios: These scenarios are dominated by renewable and sustainable energy, circular material practices, and green fabrication technologies, with minimal reliance on coal, oil, and gas. Examples include S.N.10, S.N.8, S.P.10, and S.P.8, which consistently exhibit the

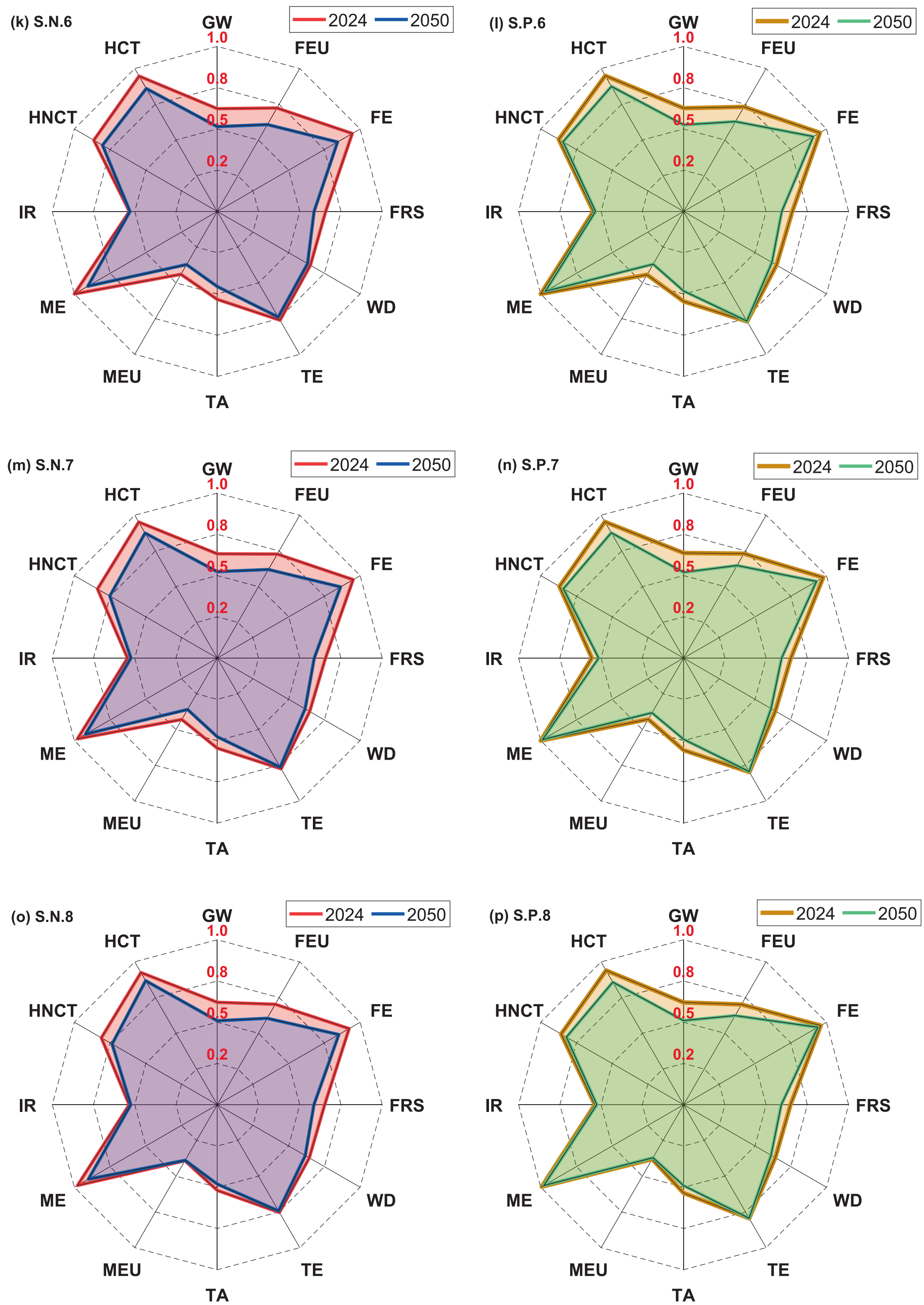

Fig. 7. (*continued*).

lowest human health (DALY) estimates by 2050 (~8.65×10^{-7}–1.20×10^{-6}). This highlights the critical role of clean electricity grids, advanced pollution control, and process efficiency in reducing health burdens. Notably, scenarios with split fabrication between low-carbon regions demonstrate intermediate health impacts, confirming that partial relocation to cleaner regions can mitigate HH risks effectively.

4.4.1.3. Temporal Performance. By 2050, the endpoint assessment shows up to ~ 60–70% reduction in HH impacts relative to 2024 levels. This reduction is more pronounced in low- and mid-impact scenarios, reflecting the combined effects of projected decarbonisation, and cleaner energy adoption. The convergence of impacts across scenarios is less complete than for midpoint categories, indicating that endpoint results integrate a broader set of environmental stressors with lingering regional differences in emissions and exposure.

4.4.2. Endpoint results – Ecosystems

The Ecosystems endpoint quantifies potential biodiversity loss

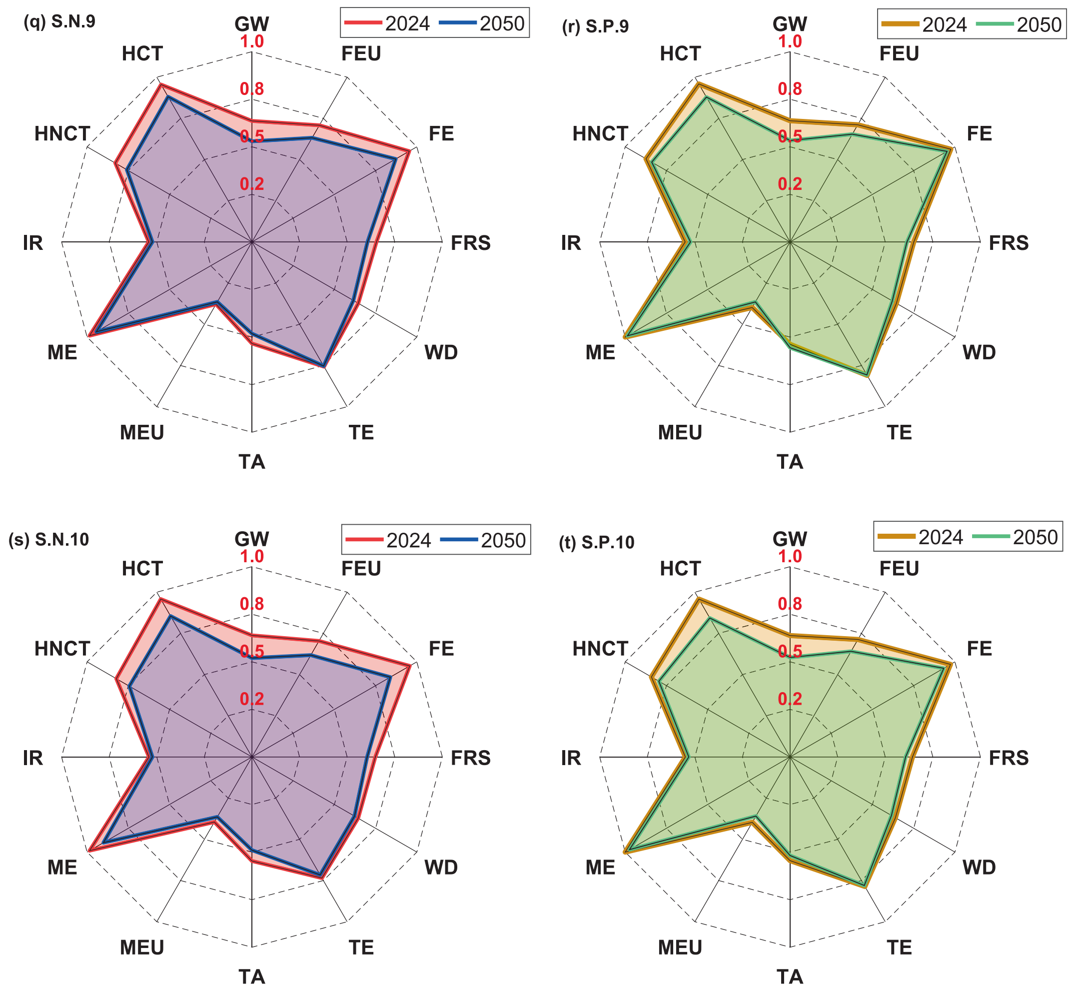

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Table 5
Absolute midpoint environmental impact results for InGaN and InGaP semiconductors under the representative scenarios S.N.1 and S.P.1 in 2024 and 2050, expressed in original units per functional unit (1 cm^2 of processed wafer).

Impact category	Unit	S.N.1 2024	2050	S.P.1 2024	2050
GW	g CO2 eq/cm^2	1771.52	424.60	1749.27	463.31
FEU	g P eq/cm^2	0.544	0.089	0.586	0.151
FE	g 1,4-DCB/cm^2	23.68	9.42	32.04	18.42
FRS	g oil eq/cm^2	426.6	107.7	418.94	114.46
WD	m^3/cm^2	0.1082	0.0494	0.1029	0.0468
TE	g 1,4-DCB/cm^2	1144.18	913.67	4679.2	4459.11
TA	g SO2 eq/cm^2	3.34	1.23	3.57	1.56
MEU	g N eq/cm^2	0.0707	0.0423	0.0801	0.0529
ME	g 1,4-DCB/cm^2	33.12	13.27	47.05	28.10
IR	Bq Co-60 eq/cm^2	35.15	29.01	39.23	33.37
HCT	g 1,4-DCB/cm^2	53.91	23.88	55.5	26.82
HNCT	g 1,4-DCB/cm^2	954.415	366.360	1504.275	942.830

associated with InGaN and InGaP compound semiconductor production, expressed in species·yr/cm^2. This metric integrates the effects of emissions on terrestrial and aquatic ecosystems, including acidification, ecotoxicity, nutrient loading, and climate-related stressors, providing a holistic assessment of environmental damage on biodiversity. Unlike midpoint indicators, which focus on specific environmental pressures, the endpoint perspective translates these pressures into potential species loss over time, reflecting cumulative ecosystem vulnerability. Fig. 8c and 8d display decreasing trend in ecosystems impacts from 2024 to 2050 across all InGaN and InGaP supply chain scenarios.

4.4.2.1. General Trends. Across all supply chain scenarios, ecosystems impacts for both InGaN and InGaP exhibit a declining trend from 2024 to 2050. For InGaN, values decrease from 6.52–8.39 × 10^{-9} species·yr/cm^2 in 2024 to 2.18–3.32 × 10^{-9} species·yr/cm^2 in 2050. InGaP shows a similar pattern with slightly higher absolute impacts (6.58–8.41 × 10^{-9} species·yr/cm^2 in 2024 to 2.42–3.52 × 10^{-9} species·yr/cm^2 in 2050), indicating marginally greater ecological pressures associated with its production processes and chemical use.

4.4.2.2. Scenario-Specific Observations. Energy-intensive scenarios: These scenarios involve substantial semiconductor fabrication in coal-dependent or otherwise energy-intensive regions (S.N.2, S.P.2). They combine high emissions of acidifying and ecotoxic substances with climate-related pressures, leading to the highest potential biodiversity loss. Partially carbon-intensive scenarios (e.g., S.N.7, S.P.7) also exhibit elevated impacts, demonstrating that even partial production in high-

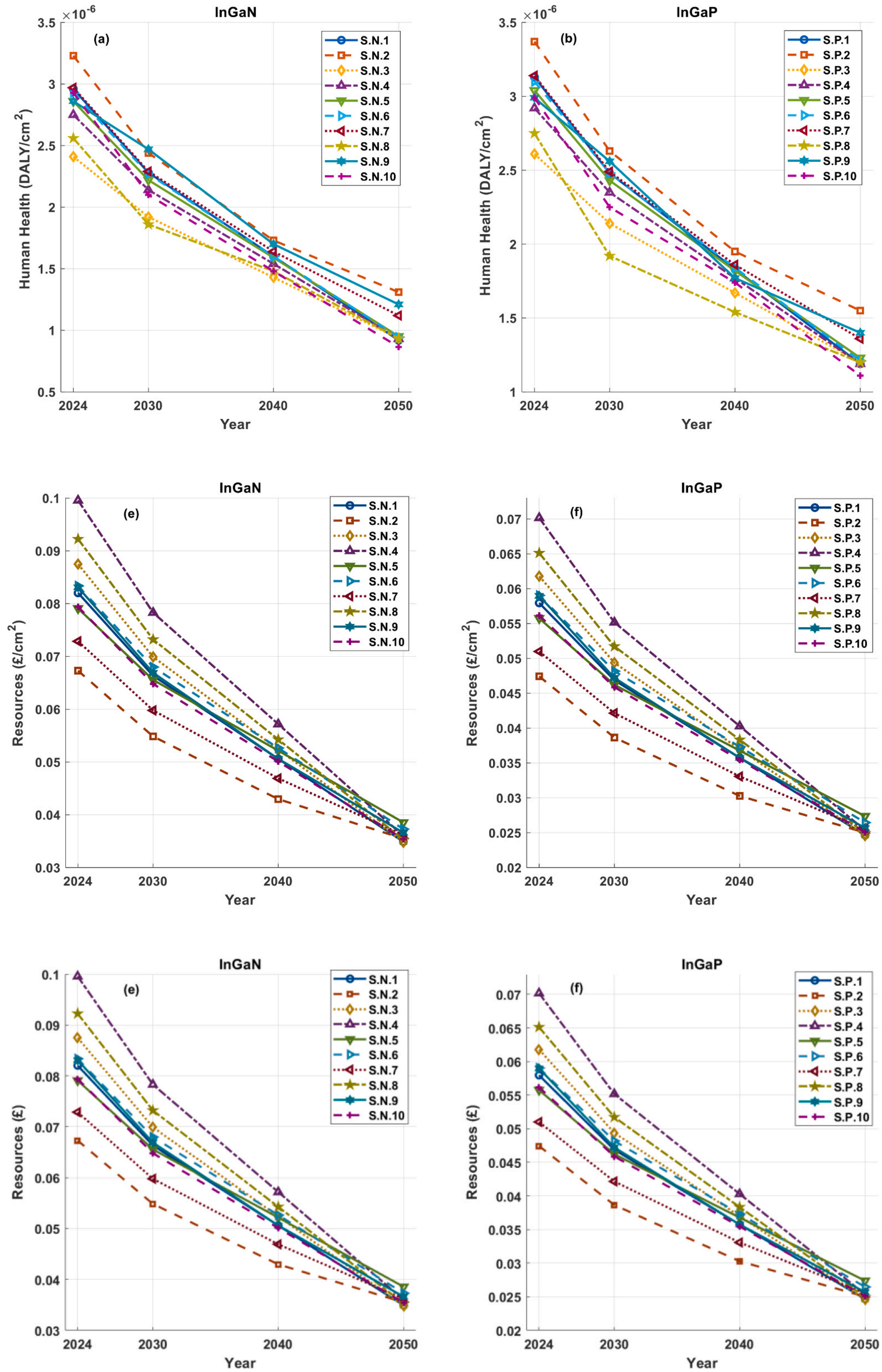

Fig. 8. Comparison of Human Health, Ecosystem, and Resource endpoint impacts for InGaN and InGaP supply chain scenarios between 2024 and 2050.

impact regions influences overall biodiversity outcomes.

Low-carbon scenarios: These scenarios are located in regions dominated by renewable and sustainable energy, circular material practices, and green fabrication, with minimal reliance on coal, oil, and gas (S.N.10, S.N.8, S.P.10, S.P.8). They consistently present the lowest ecosystem impacts by 2050 (~2.18–2.74 × 10^{-9} species·yr/cm^2). These results highlight the benefits of low-carbon electricity, efficient chemical management, and stringent environmental regulations for protecting ecosystems. Split fabrication scenarios between low-impact countries result in intermediate biodiversity effects, suggesting that geographically diversified supply chains in low-stress regions can reduce ecological damage.

4.4.2.3. Temporal Performance. The period until 2050 shows a clear reduction in potential species loss across all scenarios, with decreases of approximately 60–70% compared to 2024 values. This decline is primarily attributed to the transition toward cleaner electricity generation and a greener energy mix, which substantially reduces emissions of toxic, ecotoxic, and acidifying substances traditionally associated with fossil fuel–based power production. Endpoint convergence remains moderate; unlike midpoint categories, ecosystem impacts are still influenced by local emission profiles and regional ecological vulnerability, maintaining some differentiation among scenarios.

4.4.3. Endpoint results – Resources

The Resources endpoint quantifies the economic cost associated with the consumption of abiotic resources and critical materials in semiconductor production, expressed in £/cm^2. This metric captures the depletion of metals, minerals, and other non-renewable resources along the supply chain, translating environmental pressures into tangible monetary impacts. Unlike midpoint indicators, which focus on physical resource flows, the endpoint perspective emphasises economic consequences and scarcity implications, providing a holistic assessment of long-term resource sustainability. Fig. 8e and 8f depict a declining trend in ecosystem impacts from 2024 to 2050 for all InGaN and InGaP supply chain scenarios.

4.4.3.1. General Trends. Across all supply chain scenarios, resource impacts for both InGaN and InGaP decrease over time, primarily due to the decarbonisation of the energy mix and the associated reduction in fossil fuel extraction and processing requirements. The transition toward renewable electricity generation by 2050 reduces the embodied resource demand linked to energy supply, thereby lowering overall resource depletion impacts even without changes in material efficiency or recycling rates. For InGaN, impacts range from 0.067 to 0.100 £/cm^2 in 2024 down to 0.035–0.038 £/cm^2 by 2050. InGaP exhibits a similar declining trend, with slightly lower absolute values (0.064–0.095 £/cm^2 in 2024 to 0.033–0.037 £/cm^2 in 2050), indicating modest differences in material intensity and resource reliance between the two semiconductors.

4.4.3.2. Scenario-Specific Observations. Energy-intensive scenarios: S.N.4 and S.P.4 (USA-based fabrication scenarios) exhibit the highest resource costs in 2024. This reflects the relatively higher energy intensity of semiconductor fabrication in the USA, where electricity generation (though increasingly decarbonised) still relies partly on natural gas and fossil-based energy sources. Additionally, advanced fabrication routes and stringent purity requirements in USA facilities often entail higher consumption of critical metals and process chemicals per functional unit. Scenarios with complex or distributed supply chains (S.N.6, S.P.6) also show elevated resource burdens, suggesting that longer transport distances and multi-regional processing increase cumulative material and energy inputs, thereby amplifying resource depletion potential. Critical metals such as indium, gallium, and rare-earth elements strongly influence resource endpoint values. Scenarios with high material consumption or low recycling efficiency show higher costs.

Low-carbon scenarios: S.N.1/S.P.1 (Taiwan) and S.N.10/S.P.10 (Japan–Taiwan split) consistently yield the lowest resource-related economic impacts by 2050 (~0.034–0.035 £/cm^2). Countries with advanced semiconductor fabrication tend to have lower resource depletion costs due to optimised processes and resource recovery practices. Scenarios combining low-resource-intensity regions further reduce depletion costs, highlighting the role of supply chain planning in minimising material scarcity impacts.

4.4.3.3. Temporal Performance. By 2050, resource impacts decline by ~ 40–65% compared to 2024 levels. This reduction is primarily attributed to the decarbonisation of the energy mix, leading to lower fossil resource extraction and reduced energy-related material demand across all supply chain phases. The shift toward renewable and low-carbon electricity sources significantly decreases the embodied resource intensity of upstream processes. Endpoint convergence is notable across scenarios, reflecting the widespread effect of cleaner energy systems on resource-related burdens, although absolute differences remain due to regional variations in energy infrastructure and supply chain composition.

Endpoint indicators, including DALY for human health, species loss for ecosystems, and resource scarcity metrics, are inherently sensitive to the assumptions, characterisation factors, and weighting methods used in life cycle impact assessment models. As such, small differences between scenarios may not represent statistically significant or practically meaningful variations. These endpoint results should therefore be interpreted as indicative trends, providing qualitative insights into relative impacts rather than exact quantitative predictions.

4.5. Uncertainty analysis

Fig. 9 presents the uncertainty distributions for GW and ME for the representative scenarios (S.N.1 and S.P.1). To provide a more comprehensive representation of uncertainty, the results are visualised using a combined violin and boxplot approach based on 1000 Monte Carlo iterations. The violin plots illustrate the probability density distribution of Monte Carlo simulations, highlighting the variability and concentration of results, while the embedded boxplots indicate the median and interquartile range. This combined representation enables clearer interpretation of both the statistical spread and the distribution shape compared to conventional boxplots alone.

The wider interquartile ranges observed for 2050 reflect higher uncertainty associated with long-term assumptions on energy system decarbonisation and technological development. In contrast, the narrower distributions for 2024 indicate lower variability due to more established and well-constrained data conditions. Importantly, the separation between 2024 and 2050 distributions remains clearly distinguishable across both impact categories, indicating that the projected environmental improvements are robust under the assumed uncertainty ranges. Overall, the results suggest that the key conclusions regarding decarbonisation benefits and process improvements are not sensitive to moderate variations in input parameters, thereby reinforcing the robustness of the study findings.

4.6. Comparison with previous LCA studies and display technologies

4.6.1. Benchmarking Micro-LED technologies against incumbent display technologies

To contextualise the environmental performance of InGaN and InGaP Micro-LED technologies, this subsection benchmarks the present results against existing life cycle assessment studies of incumbent display technologies, including Liquid Crystal Display (LCD) and Organic Light-Emitting Diode (OLED), as reported in the literature.

Previous life cycle assessment studies of OLED display technologies provide an important benchmark for interpreting the sustainability performance of Micro-LED systems. These studies consistently show that, despite efficiency gains at the device level, manufacturing-related processes dominate overall environmental impacts, largely due to material- and energy-intensive fabrication steps. This observation directly supports the results of the present study, in which epitaxial growth, substrate preparation, and chemical-intensive processes emerge as the primary environmental hotspots for both InGaN and InGaP Micro-LED supply chains, even under future grid-decarbonisation scenarios [33].

More broadly, the literature indicates that technology transitions in display systems do not necessarily lead to uniform environmental improvements across all life cycle stages. In particular, studies examining the transition from LCD to OLED displays report that reductions in operational energy consumption may be accompanied by increased

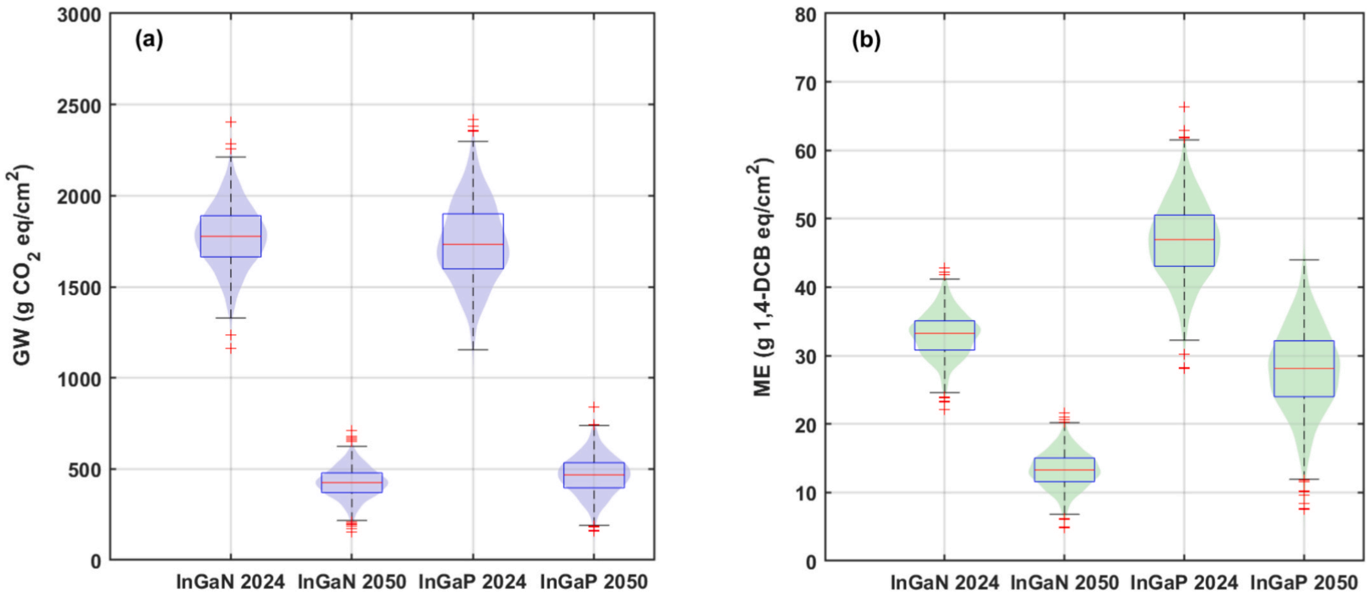

Fig. 9. Monte Carlo–based uncertainty analysis of (a) GW and (b) ME impacts for representative scenarios (S.N.1 and S.P.1).

upstream burdens, especially in materials processing and manufacturing. Consistent with these findings, the present results show that Micro-LED technologies shift a substantial share of environmental impacts toward upstream semiconductor fabrication stages, including epitaxy, photolithography, and chemical-intensive processing. Consequently, while Micro-LEDs may offer advantages in efficiency, durability, and operational lifetime, their overall environmental performance is strongly contingent on manufacturing pathways, supply-chain configuration, and end-of-life strategies, rather than on performance improvements alone [34].

Comparative assessments of legacy and modern display technologies further demonstrate that as displays become more energy-efficient in operation, the relative and absolute importance of manufacturing impacts increases. This effect is even more pronounced for Micro-LED technologies due to their reliance on advanced III–V semiconductor fabrication processes, which significantly outweigh use-phase impacts in the life cycle results presented here [35].

Another LCA study explicitly focused on Micro-LED display components further corroborate the findings of this study by identifying epitaxial growth and semiconductor manufacturing processes as dominant contributors to overall environmental impacts. Together, these results indicate that the transition from LCD and OLED to Micro-LED technologies represents technological advances that depends critically on fabrication efficiency, cleaner energy supply, and sustainable supply-chain design [36].

4.6.2. Comparison with previous LCA studies

To further contextualise the findings of this study, a comparative analysis was conducted against previous LCA studies of semiconductor and related display technologies. The benchmarking results presented in Table 6 show overall consistency between the present study and prior literature across different technology domains, despite clear differences in system boundaries, functional units, and levels of analysis.

Across semiconductor-focused studies (e.g. GaAs/GaInP solar cells and DRAM), manufacturing and upstream processes are consistently identified as key contributors to environmental impacts. This aligns with the present study, where epitaxial growth, substrate preparation, and chemical-intensive fabrication stages represent dominant environmental hotspots. Although numerical comparison is not possible due to differences in functional units and product systems, the directionality of results remains consistent across studies.

Similarly, studies on GaN power devices and III–V precursor chemicals further confirm the importance of energy-intensive fabrication processes and upstream material production. These works also highlight the sensitivity of results to electricity consumption and manufacturing energy demand, which is consistent with the observed influence of energy and process inputs in the present study. In the display technology domain (OLED, LCD, and Micro-LED studies), previous LCAs consistently emphasise the significance of manufacturing-stage impacts and detailed material inventories. End-of-life and toxicity-focused studies further reinforce the role of material composition, particularly metals and specialty chemicals, in driving environmental burdens. However, these studies differ substantially in scope and functional units, limiting direct quantitative comparison.

Overall, while previous studies span different technologies and system boundaries, a common pattern emerges semiconductor and advanced electronic devices are primarily driven by upstream material production and energy-intensive fabrication processes. The present study builds on this body of work by integrating dynamic future scenarios, international supply chain configurations, and combined midpoint–endpoint impact assessment. Importantly, this study also considers an integrated assessment of two specific technologies and their applications, which has not been simultaneously addressed in previous LCA studies, thereby providing a more application-oriented sustainability perspective.

4.7. Limitations and future research Directions

This study is subject to several limitations. The analysis assumes constant material and process inputs across all timeframes (2024–2050), with only electricity carbon intensities varying; however, future technological advancements may alter these inputs and associated impacts. Supply chain scenarios are based on fixed country assignments reflecting current global production patterns and do not account for potential geopolitical or resource-driven shifts. Transportation modelling relies on estimated distances and typical mode shares; although its overall contribution is small, minor uncertainties may remain. The use of a single functional unit (1 cm^2 of processed wafer) enables comparison but does not capture differences in device performance or lifetime. Finally, endpoint impact indicators are inherently uncertain due to modelling assumptions and should be interpreted as indicative trends rather than precise values.

Table 6
Benchmarking of Micro-LED semiconductor results against previous LCA studies of semiconductor and display technologies.

Study	Technology	Scope	Compare to this study
Mohr et al. [18]	GaAs / GaInP solar cells	LCA of thin-film III–V photovoltaic modules	Toxicity-related impact categories (e.g. marine ecotoxicity) appear as among the highest contributors based on normalised results; however, the results are not directly numerically comparable due to differences in product system, functional unit, and application domain.
Liu et al. [19]	DRAM	Manufacturing phase	Provides qualitative consistency with present study in terms of fabrication-stage dominance; however, results are not directly numerically comparable due to differences in functional unit, system boundaries, and technology type
Vauche et al. [25]	GaN power devices	Cradle-to-gate	Not directly numerically comparable due to differences in functional unit, device architecture, and scale; however, confirms that energy-intensive fabrication and cleanroom operations are key environmental drivers, consistent with the present study's findings, also confirmed results are strongly influenced by the electricity mix of the manufacturing location, leading to variability in overall impact results.
Smith et al. [28]	III–V precursor chemicals	Cradle-to-gate LCA of precursor production (functional unit: kg of chemical)	Not directly numerically comparable due to differences in functional unit, system boundary, and level of analysis (material vs device level); however, supports the importance of upstream material inputs, which are also identified as key contributors in the present study
Amasawa et al. [33]	OLED display	Cradle-to-gate LCA of display manufacturing	Not directly numerically comparable due to differences in product system, functional unit, and technology type; however, supports the importance of manufacturing-stage impacts and detailed material inventory modelling, which are also central to the present study
Yeom et al. [34]	LCD vs OLED displays	Comparative LCA + end-of-life (e-waste focus)	Results are not directly comparable due to different system boundaries (end-of-life and toxicity focus) and product systems. However, the study highlights significantly higher toxicity and resource depletion impacts associated with material composition, which is consistent with the importance of material-driven impacts observed in this study
Bhakar et al. [35]	CRT, LCD, LED monitors	full monitor over lifetime use	Not comparable due to different system boundaries, product type, and functional unit. Confirms that manufacturing processes contribute significantly to environmental impacts and that electricity consumption strongly influences overall results
Holo et al. [36]	Micro-LED display	Component-level LCA	Not comparable due to different product system, device scale, and functional unit; however, confirms that advanced display manufacturing processes are energy- and material-intensive, supporting the importance of manufacturing-stage impacts observed in this study
Present study	InGaN & InGaP Micro-LEDs	Cradle-to-gate & supply chain & energy mix decarbonisation impact in future scenarios (2024–2050)	Extends previous studies by introducing dynamic future scenarios conducting prospective LCA, international supply chain configurations, and integrated midpoint–endpoint assessment, providing a forward-looking sustainability perspective.

Future research should incorporate dynamic technological evolution, emerging semiconductor fabrication routes, recycling scenarios, and device performance integration to further improve prospective sustainability assessment. In addition, uncertainty associated with future supply chain shifts and regional policy developments should be explored using scenario-expansion and sensitivity modelling approaches.

4.8. *Policy and industry implications*

4.8.1. *Policy implications*

The combined insights from this study highlight several strategic implications for sustainable semiconductor fabrication. First, the transition from energy- to material-dominated impacts suggests that policy focus should shift from primarily promoting renewable electricity adoption to also highlighting chemical regulation and material innovation. Addressing the chemical intensity of processes will be essential to achieve further environmental gains beyond energy decarbonisation.

Epitaxial growth and substrate fabrication processes emerge as priority targets for technological intervention due to their consistently high contributions to both global warming and marine ecotoxicity impacts. Improvements in precursor utilisation, low-impact materials, and process optimisation in these phases can yield substantial reductions in environmental burdens.

Regional supply chain planning is also critical. Relocating or diversifying fabrication into low-carbon, highly regulated regions can significantly mitigate endpoint damages, highlighting the importance of geographic context in shaping environmental outcomes. Integrating circular economy approaches (such as material recovery, precursor recycling, and process redesign) can generate synergistic benefits across all impact categories. Such measures help close material loops, reduce long-term resource dependencies, and enhance overall sustainability.

Incentivise the deployment of low-carbon electricity grids in key semiconductor fabrication hubs. Support regulatory frameworks that enforce chemical and emissions management and promote circular material practices to reduce global warming and ecotoxicity impacts across the supply chain.

Finally, adopting a holistic, LCA-driven decision support framework is essential for aligning industrial, environmental, and public health objectives. This approach provides evidence-based guidance to inform policy, industrial strategy, and technological innovation, supporting the development of sustainable semiconductor supply chains through 2050.

4.8.2. Industry implications

Based on the preceding analyses of environmental impacts, process sensitivities, and regional considerations, we provide actionable recommendations tailored to specific stakeholders to guide sustainable development in compound semiconductor fabrication. Fabricators are encouraged to focus on reducing energy and chemical-related burdens through targeted interventions in high-impact process stages. Designers and material developers should prioritise material substitution, circularity, and low-toxicity precursors. Policymakers can support these efforts by incentivising low-carbon grids, promoting regulatory alignment, and facilitating innovation. The following detailed recommendations (a–i) provide specific measures for each stakeholder group to reduce environmental and resource impacts across the supply chain.

a) Prioritise low-impact epitaxial growth technologies:

Develop and adopt lower-temperature or plasma-assisted epitaxy techniques to reduce both energy consumption and emissions. Transition to renewable-powered Metalorganic Chemical Vapor Deposition (MOCVD) systems to minimize GW impacts.

b) Substitute or reformulate hazardous precursors and process chemicals:

Replace high-toxicity compounds (e.g., phosphine, arsine, and heavy-metal organics) with safer, low-ecotoxicity alternatives, and enhance chemical recovery and recycling within epitaxial growth and photolithography processes.

c) Optimise substrate materials and enable circularity:

Promote the use of recycled, thinner, or alternative substrates (e.g., GaAs, GaP, sapphire, or Si-based templates) to lower embodied emissions. Implement substrate reuse loops and recovery technologies to reduce primary material dependence.

d) Strengthen wastewater and emission control systems:

Introduce advanced effluent treatment, solvent recovery, and emission abatement systems targeting metal–organic residues and acid by-products to curb ME.

e) Improve cleanroom energy efficiency and electrification:

Continue transitioning to low-carbon electricity sources, high-efficiency HVAC systems, and smart ventilation control to sustain the observed reductions in cleanroom-related impacts.

f) Enhance process integration and yield performance:

Reduce rework and material losses by applying process intensification, AI-based monitoring, and automation, which directly decrease energy and chemical consumption per functional unit.

g) Combine decarbonisation with chemical hazard management:

Integrate energy transition strategies with green chemistry and circular material management to avoid burden shifting between GW and Ecotoxicity impact categories.

h) Promote life cycle–based supplier engagement:

Collaborate with upstream suppliers to obtain low-impact raw materials and ensure traceable, sustainable sourcing across the compound semiconductor value chain.

i) Support regulatory alignment and innovation incentives:

Encourage policy frameworks and industry standards that reward the adoption of cleaner chemistries, energy-efficient technologies, and recycling infrastructures in compound semiconductor fabrication.

5. Conclusion

This study presented a prospective cradle-to-gate LCA of InGaN and InGaP Micro-LED semiconductor supply chains under multiple international manufacturing configurations and future energy decarbonisation scenarios between 2024 and 2050. By integrating midpoint and endpoint environmental assessment with dynamic electricity-grid transition pathways, the study provided a comprehensive evaluation of the evolving sustainability performance of advanced compound semiconductor technologies.

The results demonstrate that substantial environmental improvements can be achieved through energy system decarbonisation, particularly for GW and energy-related impacts. Cleanroom-related contributions decline significantly toward 2050 across most scenarios, reflecting the influence of renewable electricity integration and lower carbon intensity grids. However, as energy-related burdens decrease, environmental impacts increasingly shift toward material- and chemical-intensive processes, particularly epitaxial growth, substrate preparation, photolithography, and testing and packaging stages. Toxicity- and ecotoxicity-related categories remain the dominant environmental hotspots throughout the assessed period, indicating that future sustainability improvements will depend not only on cleaner energy systems but also on safer chemical management, precursor substitution, process optimisation, and circular material strategies. InGaP systems generally exhibit higher toxicity-related impacts due to phosphorus- and arsenic-based precursor chemistry, whereas InGaN systems show greater sensitivity to substrate-related energy demand. The findings also demonstrate that supply chain location and electricity mix strongly influence both midpoint and endpoint results, with low-carbon and highly regulated regions consistently achieving lower environmental burdens.

Compared with previous studies, this work extends the current state of the art by combining prospective LCA, dynamic future scenarios, international supply chain configurations, and integrated midpoint–endpoint assessment within a unified framework. In addition, the study provides an integrated assessment of two specific Micro-LED semiconductor technologies and their applications, which has not been simultaneously addressed in previous LCA studies. This enables a more comprehensive and application-oriented understanding of the environmental implications of future compound semiconductor manufacturing pathways.

Overall, the study highlights the importance of adopting integrated sustainability strategies that combine energy decarbonisation with material circularity, low-impact chemical management, and environmentally optimised fabrication processes. The findings provide valuable guidance for policymakers, industry stakeholders, and researchers seeking to support the transition toward more sustainable and resilient semiconductor supply chains in future low-carbon technology systems.

CRediT authorship contribution statement

Moein Shamoushaki: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Josie Travers-Nabialek:** Data curation. **Sara-Jayne Gillgrass:** Data curation. **Peter M. Smowton:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Data curation, Conceptualization. **S.C. Lenny Koh:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

This supplementary information contains the electricity carbon intensity data used in the scenario modelling and the rationale for the exclusion of selected midpoint impact categories. Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2026.102049.

Data availability

The data that has been used is confidential.

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