



Is laser-induced graphene (LIG) environmentally sustainable? Laboratory-scale life cycle assessment of LIG from petroleum- and bio-derived precursors

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Abstract

Purpose This study explores the application of Life Cycle Assessment (LCA) to the production of laser-induced graphene (LIG), a graphene-based material obtained through direct laser ablation of carbon-rich precursors. LIG has been hailed as a sustainable alternative to conventional graphene production technologies due to the potential use of renewable feedstocks; however, no LCA has yet assessed its actual environmental performance. This study presents the first LCA of lab-scale LIG production from one petroleum-derived polymer (polyimide) and two bio-derived sources, based on maize starch and waste almond shell powder, respectively. It identifies process hotspots, focusing on energy demand and precursor contributions, and also highlights methodological challenges in early-stage LCA of emerging technologies.

Methods LIG production process from the three precursors was modeled according to a cradle-to-gate approach, using primary experimental data from laboratory measurements, to construct the Life Cycle Inventory. The functional unit is set as *the production of 1 cm² of LIG on its precursor*, meaning that LIG is not removed from the precursor after the scribing process. Environmental impacts were assessed using the Environmental Footprint 3.1 method, including all 16 impact categories, with contribution analysis for each precursor–LIG pair. The Cumulative Energy Demand (CED) was also calculated and compared to other graphene production routes. Lastly, sensitivity analysis was performed, exploring two renewable energy scenarios to assess potential improvements.

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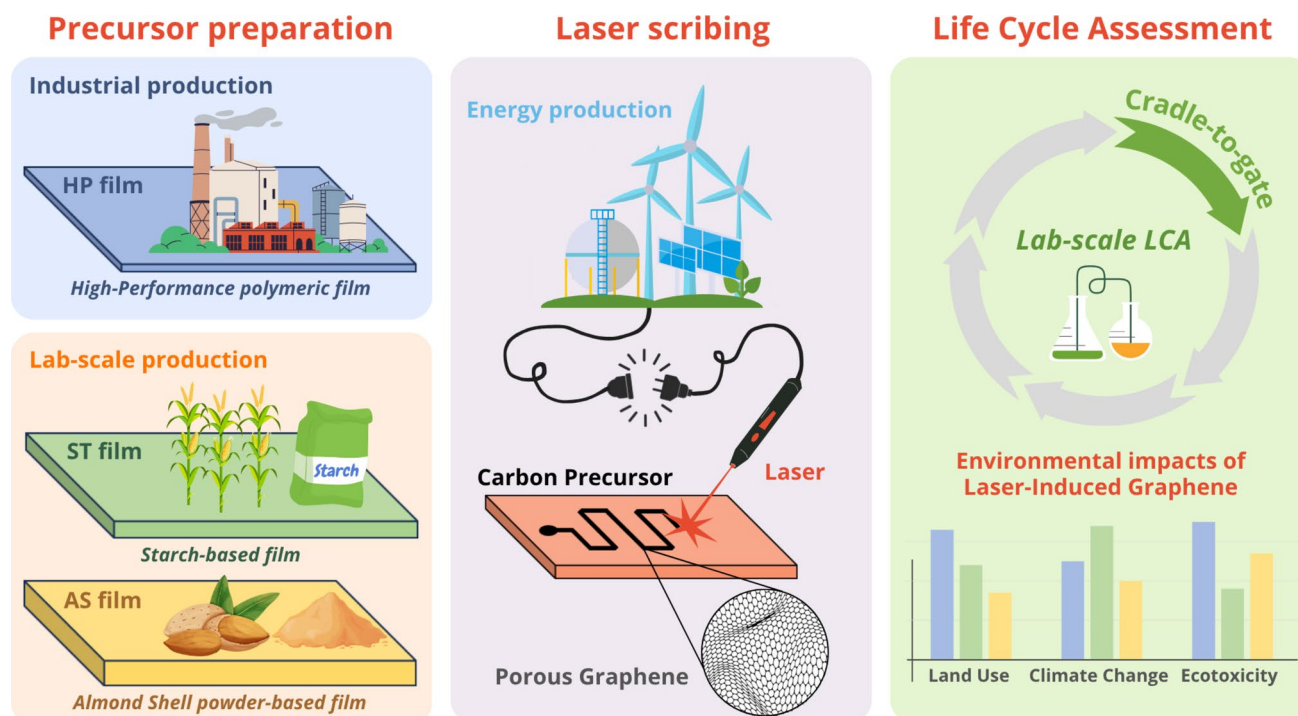
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Results and discussion Results show that laser energy use is the primary environmental impact driver for LIG production, outweighing the influence of precursor type. As a result, the potential benefits of using bio-derived precursors are not yet captured, as they currently only influence the selection of optimal laser writing parameters. Also, LIG resulted comparable to other graphene production methods in terms of energy demand. At the current technological maturity, the transition toward energy-efficient solutions represents the key step for optimizing the environmental sustainability of the LIG production process.

Conclusion Laser scribing, often proposed as a sustainable approach for graphene synthesis, currently suffers from high energy intensity that offsets the benefits of using renewable precursors. However, results may vary if system boundaries are extended to a cradle-to-grave analysis, eventually considering process scale-up scenarios and including data on the human and environmental toxicity of graphene-based materials. While these aspects cannot yet be integrated into the LCA of LIG production, this study represents a first step toward a clearer understanding of its environmental impact, hopefully contributing to advancing its technological readiness level.

Graphical Abstract



Keywords LCA · Bio-based · Fossil-based · Starch · Waste almond shells · Laser scribing

1 Introduction

Since 2004, graphene and graphene-based materials (GBMs) have gained significant attention thanks to their unique properties such as high electrical conductivity, thermal stability, and mechanical strength (Novoselov et al. 2004). These characteristics make graphene and GBMs promising candidates for various applications, from electronics and optoelectronic devices to composite materials, fuel cells, water treatment, energy storage, sensors, and biomedical applications (Yuan et al. 2023). However, one major limitation to the applicational development of graphene and GBMs is the optimization of industrially scalable production processes to provide high-quality graphene. Two approaches can be

defined, namely top-down and bottom-up. The top-down approaches involve the structural breakdown of a precursor, such as graphite, followed by interlayer separation to produce graphene sheets. This category includes mechanical exfoliation (Novoselov et al. 2004), liquid-phase exfoliation (LPE) (Hernandez et al. 2008; Lozano-Chico et al. 2024), oxidation–reduction of graphene oxide (GO) (Shang et al. 2015), and arc discharge (Wu et al. 2016). Bottom-up approaches, instead, consist of synthesis starting from a carbon source precursor, which is then converted into graphene. These methods include chemical vapor deposition (CVD) (Reina et al. 2009), epitaxial growth (EPI) on silicon carbide (Yazdi et al. 2016), and catalytic graphitization (Hunter et al. 2022). Usually, top-down processes produce

graphene rich in imperfections and with lower properties than graphene produced using bottom-up methods. The latter, however, result in lower production volumes and are more resource-intensive.

In 2014, a new innovative approach based on transformative direct laser writing (DLW) was proposed. Laser-induced graphene (LIG) was obtained by laser irradiation of commercial polymers such as polyimide (PI) and polyetherimide (PEI), using a CO₂ infrared laser (Lin et al. 2014). The laser induces chemical and structural changes in the precursor material via a fast pyrolytic process, driven by the high temperature (> 2400 K) and pressure (≈ 3 GPa) generated at the beam focal point on the precursor surface (Dong et al. 2016). A plasma is created locally, generating outgassing of byproducts from the target material, leaving behind a concentrated layer of carbon atoms that rearranges from a sp³ to a sp² hybridization to form a graphenic structure (Zhang et al. 2023). Unlike the perfect 2D crystal structure obtained from bottom-up methodologies, LIG presents a three-dimensional porous structure, which comprises amorphous regions and defects such as five- and seven-membered carbon rings (Lin et al. 2014). Additionally, heteroatoms (e.g., oxygen, nitrogen) are bonded to the edges of the graphene layers, resulting in a mixed polygonal arrangement (Lin et al. 2014; Dong et al. 2016). Despite these structural differences from pristine graphene, LIG presents a large specific surface area (~ 340 m² g⁻¹), high thermal stability (> 900 °C), excellent conductivity (5–25 S cm⁻¹) (Lin et al. 2014), and can be easily patterned on both flexible and rigid precursors, making it suitable for applications in sensors, energy devices, environmental protection and remediation techniques, and biomedicine (Zhang et al. 2023).

LIG discovery represented an incredible step forward in the carbon nanomaterials scene for many reasons. First, the laser scribing process is typically carried out in air, under ambient conditions, without the need for single-use masks or hazardous chemicals or solvents, high-temperature processing, and/or vacuum apparatuses. Secondly, the process is fast and fully customizable, as LIG can be produced according to any computer-designed pattern. Lastly, conductive LIG tracks can be scribed on insulating precursors, a desirable feature for soft/flexible/printed electronics applications, where the precursor also acts as the substrate of the final device. Many precursors can be converted into LIG, provided that they encounter two key requirements, i.e., being carbon-rich and thermally stable, to withstand high temperatures without being fully ablated during the laser scribing. These materials typically contain aromatic, imide, or aliphatic repeating units (Claro et al. 2022). Moreover, strong film-forming ability in these precursors is advantageous for applications of the resulting LIG in flexible electronics. Many sources of carbon meet these prerequisites, and researchers have been producing LIG from a wide variety

of precursors, both petroleum-derived (e.g., polyimides (Lin et al. 2014), polyetherimides (Lin et al. 2014), polysulphones (Singh et al. 2018), polyetheretherketone (Zhu et al. 2019)) and bio-derived (e.g., wood, paper, potato skins, starch, almond shells) (Chyan et al. 2018; Claro et al. 2022; Bressi et al. 2023; Lengger et al. 2024; Sankaran et al. 2024; Steksova et al. 2025). In recent years, there has been a significant shift of interest from petroleum-derived to bio-derived precursors, driven by the possibility of exploring the application of LIG in so-called transient electronics. These devices are designed to disintegrate with minimal and non-harmful remains and have been extended to areas such as bioelectronics, environmental monitoring, energy harvesting, and storage (Fu et al. 2016). In this context, the degradability of LIG produced from bio-derived precursors can be tailored for specific applications, potentially reducing end-of-life electronic wastes (Bressi et al. 2023).

For these reasons, there has been a significant increase in the use of terms such as “green LIG”, “sustainable LIG”, or claims that the LIG production process is more sustainable or environmentally friendly than other graphene production processes, especially when a bio-derived substrate is used as a precursor (Claro et al. 2022; Vaughan et al. 2023; Zhang et al. 2023; Moon and Ryu 2024; Silvestre et al. 2024). Despite the apparent reasonableness of these claims, a product cannot be automatically considered sustainable because it is made of bio-derived materials or is biodegradable since there is a difference between *product sustainability* and *process sustainability*. Indeed, product sustainability focuses on the environmental impact of the entire lifecycle of the product, from raw material extraction to manufacturing, use, and end-of-life management, including recycling or disposal. On the other hand, process sustainability specifically evaluates the environmental performance of the production process itself, such as the resources and energy consumption, emissions, and generated waste (Huang and Badurdeen 2017). Therefore, a process that uses renewable resources or bio-derived materials might still have a significant environmental footprint due to high energy requirements or the release of pollutants (Weiss et al. 2012; Torres et al. 2021). Also, there is a wide variety of bio-derived and/or degradable precursors for LIG production (Claro et al. 2022; Bressi et al. 2023), each with its unique chemical-physical characteristics that influence the final properties of the LIG and consequently the possible fields of application. It is therefore unreasonable to define a priori that both LIG and its production process are “more sustainable” than other types of technologies for GBMs.

A solution to these dilemmas can be found by exploiting the quantitative rigor of Life Cycle Assessment (LCA), a scientific methodology for evaluating the potential environmental impacts associated with all stages of the life cycle of a product, process, or service (ISO 14040 2006); ISO 14044

Table 1 Non-exhaustive list of previous LCA studies on graphene production processes, summarizing the production method, functional unit, impact categories, LCIA (Life Cycle Impact Assessment) method, database utilized, and the hotspot, i.e., main source of impacts

| References | Production method | Functional unit | Impact categories considered | LCIA Methods | Database | Hotspot |
|----------------------------------------------------------|--------------------------------|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|-------------------------------------------|----------------------------------------|
| Arvidsson et al. (2014) | Chemical reduction | 1 kg | Energy use, water use, toxicity, and ecotoxicity | USEtox | ecoinvent v2.2 | Reduction step (i.e. Hummers' process) |
| Arvidsson et al. (2016) Arvidsson and Molander (2017) | Exfoliation by ultrasonication | 1 kg | Energy use and metal use Energy use, climate change, acidification and ecotoxicity climate change, ozone depletion, human toxicity, respiratory inorganics, ionizing radiation, photochemical ozone formation, acidification, eutrophication, ecotoxicity, land use, and resource depletion | EPS 2000, CED | ecoinvent v2.2 ecoinvent v2.2 | Exfoliation solvent production |
| | Chemical vapor deposition | 1 cm ² | | CED, ReCiPe, USEtox | | Chemical precursor production |
| | Chemical reduction | 1 kg | | ILCD | | Substrate production |
| | Thermal reduction | 1 kg | | | | Energy demand |
| Cossutta et al. (2017) | Electrochemical exfoliation | 1 kg | | | | Energy demand |
| | Chemical vapor deposition | 1 cm ² | | | | Energy demand |
| | | | | | | Energy demand |
| Khanam (2017) | Biotechnological method | 1 kg | climate change, acidification, eutrophication, ozone depletion, abiotic depletion, freshwater ecotoxicity, human toxicity, marine ecotoxicity, terrestrial ecotoxicity, photooxidant formation land use, and resource depletion | CML 2001 | GaBi database | Production of graphene oxide |
| Jia et al. (2022) | Flash Joule heating | 1 g | climate change, fossil depletion, terrestrial acidification, freshwater eutrophication, metal depletion, particulate matter formation, photochemical oxidant formation, and water depletion | ReCiPe 2008 | ecoinvent v3.5, PE international database | Energy demand |

2006). LCA has been previously used in the nanomaterials sector, also including some graphene production processes (Salieri et al. 2018). Table 1 summarizes some of the works that attempted to estimate the environmental impacts of graphene and GBMs' production processes by means of LCA. From a methodological perspective, several trends can be outlined in the way LCA has been applied in previous studies. First, two functional units are most commonly used: one mass-based and one based on surface area. This is because the considered processes result in very different production volumes: for example, 1 g of graphene obtained by reduction of GO appears as a dark powder that can be weighed on a laboratory balance, while 1 g of monolayer graphene produced by CVD would occupy a surface area of about 1600 m² (about the size of three tennis courts) (Guoqing et al. 2011). Each LCA study relies on different data sources, databases, system boundaries, calculation methods, and environmental impact categories, which hinder an objective comparison between the various processes. Some studies also attempted to simulate process scale-up, but each based on different assumptions (Arvidsson and Molander 2017; Cossutta et al. 2017). However, despite these differences, all analyzed studies are cradle-to-gate, i.e., they include resource extraction and production, without considering use or end-of-life. The reasons are related to the very diverse potential applications of GBMs and the variability of the possible end-of-life and disposal routes (Hong et al. 2022). Furthermore, in the context of relatively low industrialization for this sector, it is more useful to investigate the life cycle of the production process rather than the product.

In 2021, with the European Commission's research initiative *Graphene Flagship* (2013), an attempt was made to clarify the current state of research related to LCAs of graphene production. Within this project, Beloin-Saint-Pierre and Hirschier (2021) re-calculated impacts from previous studies according to the authors duly acknowledged some critical shortcomings in the proposed model, such as the omission of considerations regarding functional properties and potential toxicity of GBMs. Nevertheless, their work marked a significant advancement in LCA research on graphene production processes.

Given these premises, LCA methodology appears as a valuable tool for solving the sustainability conundrum of new GBMs' production processes, including LIG. While LIG has been integrated into previous LCA-related studies (Liu et al. 2023; Morais et al. 2024), to the best of our knowledge, no work has provided a detailed and process-specific environmental assessment of LIG production itself. Thus, the aim of this study is to perform for the first time an LCA of the laboratory-scale production process of Laser-Induced Graphene, according to a cradle-to-gate model, including the comparison between petroleum-derived and bio-derived precursors. The LIG production process

is also compared to other graphene production technologies, by comparing the corresponding Cumulative Energy Demands (CED). In addition, a sensitivity analysis is performed, evaluating the influence of two alternative energy scenarios on the overall environmental performance of LIG production. Lastly, starting from the LIG case study, the limits and potentials of the LCA methodology applied to the laboratory context have been analyzed, discussing the role of modeling assumptions, uncertainties related to the production scale, and the prospects of transferability of the results to industrial contexts.

2 Methods

2.1 Experimental set-up

This work compares the environmental impacts of LIG produced from three different precursors. The first precursor is a commercially available high-performance petroleum-derived PI film, which represents the benchmark for the production of LIG (hereafter called "HP film"). The second precursor is a bio-derived starch-based polymer (ST film), and the third is a bio-derived chitosan-based matrix, containing waste almond shell powder (AS film). Both bio-derived precursors are prepared by LAMPSE (Laboratory of Applied Materials for Printed and Soft Electronics), at the Biorobotic Institute of Sant'Anna School of Advanced Studies in Pisa (Italy), in the context of ongoing research projects for the development of new LIG precursors and LIG-based devices. ST film is mainly composed of starch, while AS film contains powdered waste almond shells, dispersed into a chitosan matrix. Both these materials are bio-derived and degradable in soil (Sankaran et al. 2024; Steksova et al. 2025). The rationale behind the selection of these three precursors lies in our intent to explore the implications of material origin in the context of environmental sustainability. The HP film serves as a synthetic benchmark, widely adopted in LIG research due to its more established laser scribing conditions and high-quality graphene yield. In contrast, the ST and AS films represent two classes of bio-derived alternatives: ST is based on an industrially processed polymer (starch), whereas AS integrates a matrix with an agricultural waste product (almond shells). While almond shells' availability may be regionally variable, they nonetheless represent an abundant non-edible lignocellulosic feedstock (global annual production volume \approx 800,000 tons (Almond Industry Statistics 2024)) that does not require additional land use or cultivation inputs. Additionally, the precursors' selection was influenced by the availability of primary experimental data, enabling a consistent and directly comparable assessment of laser scribing and material characterization across all three materials. Table 2 shows the weight compositions of the LIG

Table 2 Compositions of LIG precursors (wt%) in the three considered cases, High Performance polymeric (HP), STarch (ST), and Almond Shell powder (AS) films, and operating conditions for laser scribing 1 cm² of LIG. The laser operates with a maximum power output (laser power) of 50 W and a maximum scanning speed (speed) of approximately 250 mm/s

| Precursor | | Laser operating conditions | | | |
|-----------|-------------------------------------------------------------------------------------|----------------------------|-----------|-------------------|-------------------------|
| Sample | Components (concentration, wt.%) | Laser power [%] | Speed [%] | Scribing time [s] | Energy consumption [Wh] |
| HP film | Kapton HN 200, purchased from DuPont (100%) | 10 | 10 | 66 | 13.9 |
| ST film | Maize starch (39%) Glycerol (25%) Acetic acid (20%) Iron nitrate (16%) | 15 | 10 | 66 | 14.2 |
| AS film | Almond shells powder (35%) Glycerol (28%) Acetic acid (19%) Chitosan (18%) | 10 | 10 | 198 | 41.5 |

precursors analyzed in this work, together with operating conditions for scribing 1 cm² of LIG on each of them.

Kapton HN 200 film (thickness 50 μm) is purchased from DuPont (HP film). The ST film (thickness 250 μm) is prepared by mixing starch with glycerol, acetic acid, water, and iron nitrate, according to the procedure described in Sankaran et al. (2024). An energy optimization was performed with respect to the original work by producing bigger batches in beakers with a larger bottom surface to increase thermal exchange during stirring. The AS film (thickness 600 μm) is prepared by mixing waste almond shell powder and chitosan with water, glycerol, and acetic acid, as reported in Steksova et al. Again, an energy optimization has been carried out with respect to the original work by reducing the stirring time from overnight (10 to 15 h) to 7.5 h, which still ensured a homogeneous mixture. For both ST and AS precursors, mixtures are cast and dried under ambient conditions.

To produce LIG, for each precursor, 1 cm² of film is cut and placed in a commercially available CO₂ Infrared laser scribing machine (Universal Laser Systems VLS 3.50). Scribing conditions (Table 2) are reproduced from previous works (Dallinger et al. 2020; Sankaran et al. 2024; Steksova et al. 2025), in which they have been optimized for each precursor. A plug-in power meter was used to measure the relative energy consumption. LIG produced from the three precursors was analyzed to confirm the correct formation of porous graphene. Samples were subjected to Raman analysis (LabRAM HR Evolution), scanning electron microscopy (SEM, ThermoFisher Tecnai TF 20 X-TWIN), and resistivity measurements (Keithley 2604B source meter), confirming the conversion of all the samples into LIG (Sect. 1 of Supporting Information).

2.2 Life Cycle Assessment (LCA)

2.2.1 Goal and scope definition

This work aims to evaluate the potential environmental impacts associated with LIG production, highlighting hot-spots and critical aspects along all the process stages, and considering alternative energy scenarios. Additionally, we aim to compare the environmental impacts of LIG production to those of other conventional graphene production technologies.

The functional unit is *the production of 1 cm² of LIG on its precursor*, meaning that LIG is not removed from the precursor after the scribing process. The reason for this choice lies in the intrinsically innovative nature of LIG; in fact, this technique allows for the synthesis and patterning of conductive surfaces on non-conductive precursors, without the need to transfer the graphene to another substrate. In this work, we deliberately omitted functional properties (e.g., conductivity, Raman peak intensity ratio, morphological features) within the definition of the functional unit. Indeed, in accordance with previous studies (Arvidsson and Molander 2017; Beloin-Saint-Pierre and Hischier 2021), depending on the technique chosen, the properties of the graphene produced vary, as does the relative possible application. However, even if functional properties are not declared in the definition of the functional unit, in Sect. 1 of Supporting Information, we report the characterization analyses to confirm the successful formation of LIG. Briefly, while the LIG obtained from the three precursors is broadly comparable in terms of morphology and properties, some minor differences can be observed. All LIG samples exhibit high porosity, but LIG-HP shows a higher degree of macrostructural order, based on a qualitative

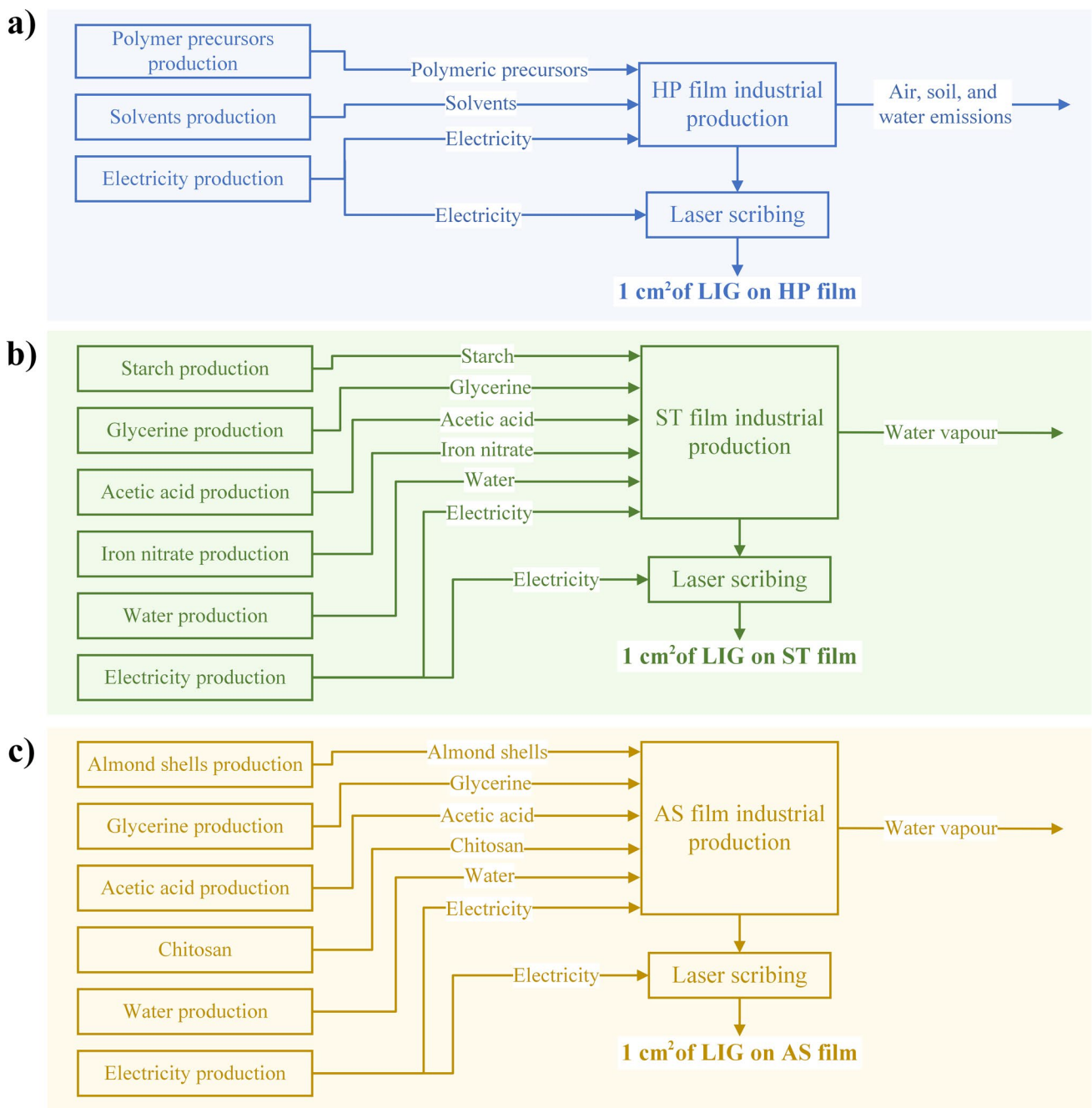


Fig. 1 System boundaries of the LCA study, including precursors preparation and laser scribing of **a** HP film, **b** ST film, and **c** AS film. Emissions from HP film production are generically reported as “air,

soil, and water emissions” due to the use of an aggregated dataset, whose further details are provided in the Supporting Information

visual inspection, whereas LIG derived from ST and AS films appears more disordered. Raman spectroscopy reveals that LIG-HP and LIG-ST have lower I_D/I_G ratios (1.1) compared to LIG-AS (1.4), indicating fewer structural defects. The I_{2D}/I_G ratios are similar across the samples, ranging from 1.4 to 1.6. For what concerns the electrical resistance, LIG-HP exhibits the lowest resistance (0.19 k Ω) for resistors with dimensions

40 mm \times 5 mm, outperforming LIG-ST (59.40 k Ω) and LIG-AS (4.07 k Ω).

Due to the low technology readiness level (TRL) of LIG, its potential applications, use patterns, and end-of-life scenarios are still highly uncertain and diverse. For these reasons, the study is performed from cradle to gate, focusing on the environmental impacts of the production phase. System

boundaries are represented in Fig. 1 and cover two main phases: precursor preparation (i.e., HP film industrial production, ST film lab production, and AS film lab production, for HP, ST, and AS film, respectively) and laser scribing. These two phases constitute the foreground system and take place in Italy, where the laboratory is situated. Emissions related to the laser scribing process were not represented within the system boundaries. As mentioned in Sect. 2 of Supporting Information, although high temperatures during laser-induced pyrolysis can release gases (e.g., CO, CO₂, H₂O, H₂, NO_x), their quantities are minimal (Dong et al. 2016) and considered negligible in terms of environmental impact. Storage and handling of waste materials were excluded from the system boundaries. Additionally, since LIG can be considered an immature product, from the point of view of its industrialization, we decided to exclude transportation from the system boundaries and model background processes using secondary data from market datasets (Beloin-Saint-Pierre and Hirschier 2021). This choice is common in many LCA studies on graphene, as including specific data for background processes may be misleading for immature products. Indeed, the background context may change when the product becomes commercially mature (Arvidsson et al. 2014; Arvidsson and Molander 2017; Cossutta et al. 2017; Jia et al. 2022).

2.2.2 Life Cycle Inventory (LCI)

The LCI was constructed using primary data from laboratory measurements, together with secondary data from literature and databases. Ecoinvent v3.10 cut-off version (ecoinvent 2023) was used as the reference database for this study. In cases where specific datasets were unavailable, complementary data were sourced from Agribalyse-unit version 3.1.1 (ADEME 2023) and carbonminds (cm.chemicals Plastics) (carbonminds 2024). Calculations were performed with SimaPro software version 9.6 (PRé Consultants 2024), according to the attributional methodology (PRé Consultants 2024). In the following section, we briefly describe the key modeling choices and assumptions for each precursor and the corresponding LIG. More details, including the specification of the databases used to model the input flows, are reported in Sect. 2 of Supporting Information.

For bio-derived LIG precursors, ST film and AS film inventories were based on primary data from laboratory measurements. For the ST film, all inventory components were taken from the ecoinvent database and used as such (market datasets). For the AS film, chitosan was modeled starting from the work of Riofrio et al. (2021), while almond shells were considered burden-free, and only the energy for their grinding was considered. The Italian electricity mix (ecoinvent 2023) was used for modeling laboratory operations, including laser

scribing to produce LIG, using primary data from direct measurements of instruments' energy consumption (see Table 2). Concerning the petroleum-derived precursor (HP film), no specific datasets for polyimides were found in existing LCA databases, nor were any literature studies identified that modeled their production process. Therefore, we decided to rely on a proxy using the polyetherimide (PEI) dataset available in the carbonminds database (carbonminds 2024). This choice is justified considering that the two polymers present an aromatic backbone and imide linkages leading to similar rigidity and thermal stability, and were both reported as LIG precursors (Lin et al. 2014).

To fulfill the selected functional unit, we considered that the scribing process is performed on 1 cm² of precursor, in the form of film (HP film, ST film, and AS film). The three films are characterized by different compositions and mechanical properties, but most of all, they present very different thicknesses. For this reason, 1 cm² of each precursor will have a different weight, since a different amount of material is required to fulfill the surface-based functional unit. For the sake of completeness, we compared the environmental impact of the three precursors, considering both the abovementioned functional unit (1 cm²) but also a mass-based functional unit (1 g), to better understand the role of precursor choice on the overall impacts of LIG production. Detailed information on LCI is reported in Sect. 2 of Supporting Information.

2.2.3 Life Cycle Impact Assessment (LCIA)

Three LCIA methods have been used in this work. The Environmental Footprint (EF) 3.1 (version 1.01) has been chosen as reference since it is the impact assessment method adopted by the European Commission's Environmental Footprint transition phase (European Commission 2023). It covers 16 environmental impact categories, including climate, ecosystems, human health, and resource depletion. Then, we used the Cumulative Energy Demand (CED) method (version 1.12), which provides the total amount of primary energy consumed throughout the lifecycle (Frischknecht et al. 2015). This method, previously adopted in the literature for LCA of graphene production processes, was selected to compare LIG's environmental impacts with those reported in previous studies (Arvidsson et al. 2016; Arvidsson 2017; Arvidsson and Molander 2017; Serrano-Luján et al. 2019). We also performed a sensitivity analysis using the ReCiPE 2016 method (version 1.09) (RIVM et al. 2016) to confirm results from the EF method concerning LIG production. Impact assessment results were reported in Excel documents for further calculations (see Sect. 3 of Supporting Information).

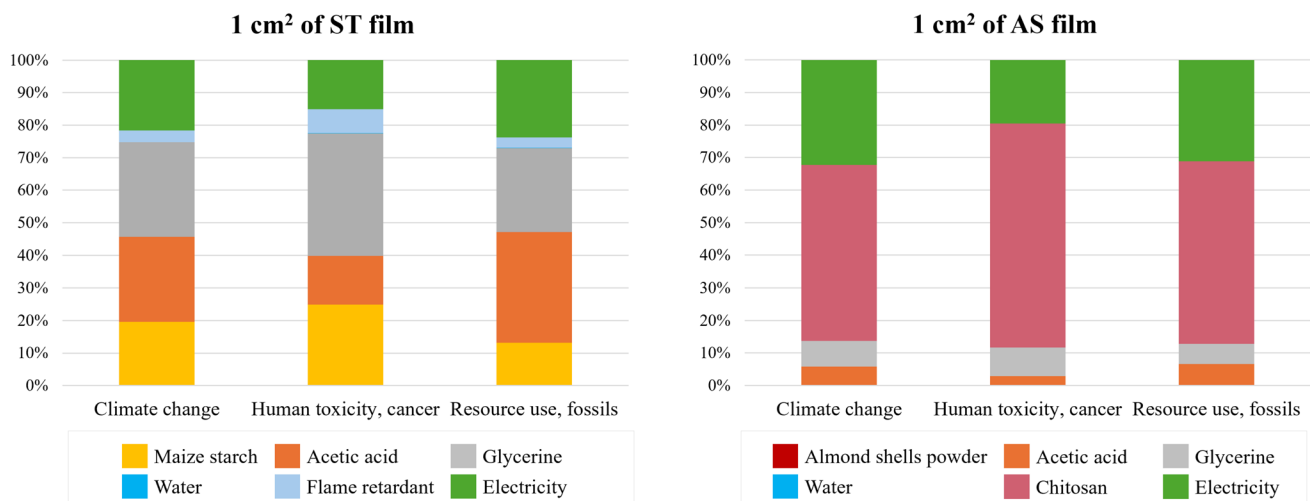


Fig. 2 Contribution analysis for the production of 1 cm² of bio-derived film precursors: ST film (left) and AS film (right). The LCIA method used is Environmental Footprint (EF) 3.1

2.2.4 Life cycle interpretation

The interpretation of results was performed starting from the framework proposed by Beloin-Saint-Pierre and Hischier (2021), considering the following steps: (i) contribution analysis of both precursors and LIGs; (ii) comparison of the three LIGs; (iii) comparison of LIG with other graphene production processes; (iv) sensitivity analysis concerning alternative energy scenarios.

Contribution analysis represents the fundamental step for the identification of the most significant contributors to the overall environmental impacts. It determines which inputs, processes, or life cycle stages are responsible for the greatest environmental burdens, enabling hotspot identification. We decided to perform contribution analysis both on LIGs and precursors production processes, to deepen our knowledge of hotspots along all stages of LIG production. A comparison of the environmental impacts of the three LIG production processes was then conducted, focusing on the influence of scribing parameter variations, which are tailored according to the physicochemical nature of the precursor. We also compared the CED of LIG with that of other graphene production processes, reported in the literature, with the functional unit of 1 cm² of graphene. Finally, we conducted two sensitivity analyses concerning energy inputs to understand how environmental impacts may change in an energy-efficient context. Firstly, as previously done by Cossutta et al. (2017, 2020), we used the Norwegian electricity mix to represent a future “best-case scenario” of decarbonized electricity production. Indeed, the Norwegian electricity mix is based on about 99% renewable resources (mainly hydropower and wind) (IEA 2022; ecoinvent 2023). Secondly, we modeled the

2030 Italian electricity mix, based on data from the PNIEC scenario (Integrated National Energy and Climate Plan) (Carvalho et al. 2020, 2022), which represents a realistic scenario for the progressive decarbonization of the Italian energy sector. Compared to the composition of the Italian electricity mix of 2020 (from ecoinvent), which was used as the baseline for the simulations in this work, the forecast for 2030 presents a reduction in the use of fossil fuels such as gas and oil, in favor of renewable sources, such as solar, geothermal, and wind. Detailed information on the modeling of energy scenarios is reported in Sect. 2 of Supporting Information.

3 Results and discussion

This section presents the main results of the study and discussion, organized into five subsections: contribution analysis (3.1), comparison (3.2), comparison of LIG with other graphene production processes (3.3), sensitivity analysis concerning alternative energy scenarios (3.4), and methodological limitations and recommendations (3.5). Sub-Sects. 3.1 and 3.2 are further divided into two parts, addressing respectively the contribution analysis and comparison of the precursors (3.1.1 and 3.2.1) and of the LIGs (3.1.2 and 3.2.2).

3.1 Contribution analysis

3.1.1 Precursors

Since HP film was taken from an aggregated dataset, constructed as a cradle-to-gate aggregation of all environmental

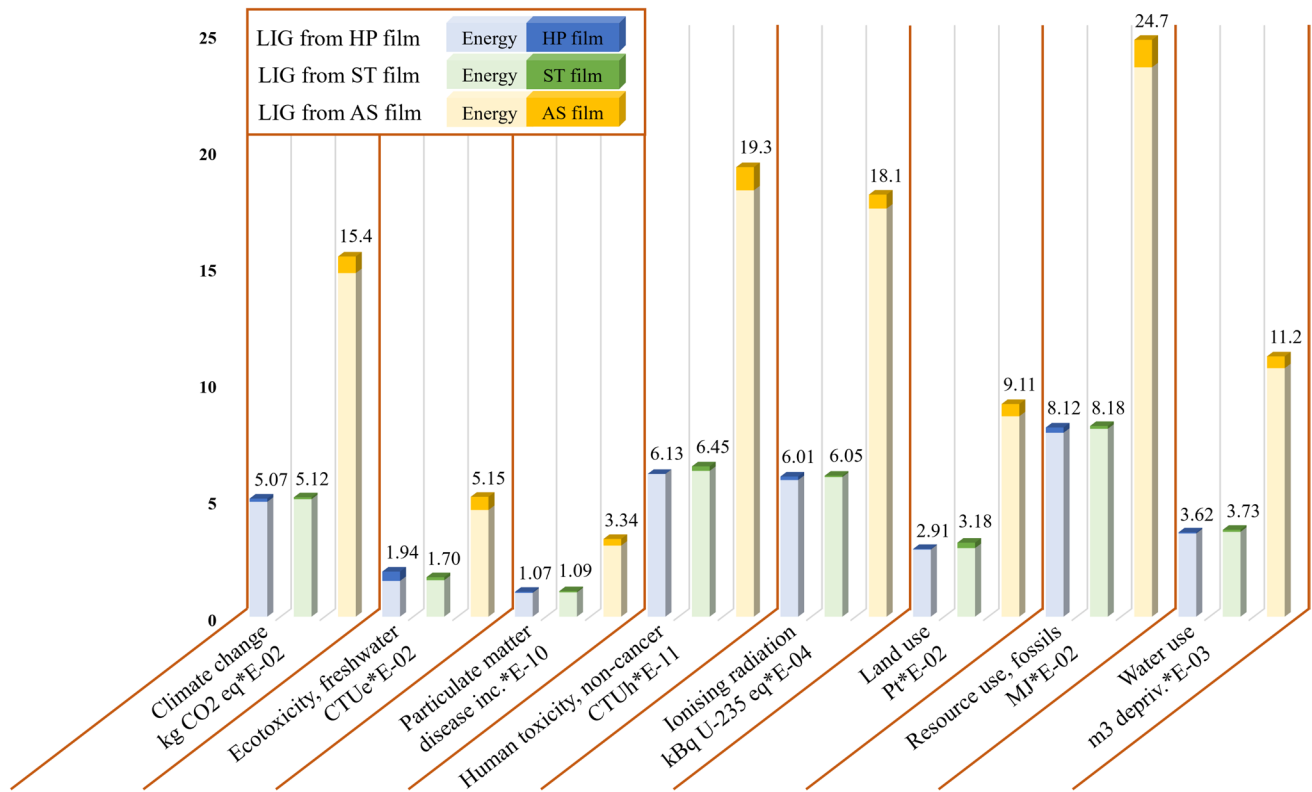


Fig. 3 Comparison of environmental impacts of the production of 1 cm² of LIG from the three precursors (HP film, ST film, and AS film) including the contribution of precursors and energy use for laser scribing. The LCIA method used is Environmental Footprint (EF) 3.1

flows for the reference product, we could not perform a contribution analysis on its production process but only compare its overall impacts with those of other precursors. ST film and AS film laboratory production were instead modeled at the unit process level with primary data. The highest contributions to the environmental impacts associated with the preparation of 1 cm² of ST film (33.5 mg) are distributed mainly between glycerine, acetic acid, and maize starch. Concerning glycerine and acetic acid, this is due to their chemical synthesis at the industrial level. Maize starch instead contributes most to categories related to maize cultivation, such as land use and water use. A relevant contribution is also due to electricity use for stirring and heating operations. For the preparation of 1 cm² of AS film (67.7 mg), the major contribution to all impact categories is associated with chitosan. This is because high amounts of sodium hydroxide and hydrogen chloride are required for chitosan production; thus, its environmental burdens are relevant, even if chitosan is produced from waste bio-derived material, such as shrimp shells. The second highest contribution for AS film production comes from electricity use; this is due to the laboratory procedure, which requires stirring the solution for 7.5 h. Figure 2 reports contribution analysis for the production of 1 cm² of ST film and AS film, including Climate change, Human toxicity (non-cancer), and Resource use (fossil), which are the ones most often reported

in the literature (see Table 1). The contribution analysis for the complete list of impact categories is reported in Sect. 3 of Supporting Information.

3.1.2 LIG

Concerning LIG production from each precursor, contribution analysis revealed the energy-intensiveness of the process; on average, electricity use for laser scribing contributes more than 90% to all impact categories (Fig. 3). The HP film precursor contributes more than 10% only to marine eutrophication, ozone depletion, and particulate matter formation, and the reasons can be linked to the polymer production process. On the other hand, when considering LIG from both bio-derived materials, precursors contribute on average less than 10% to all impact categories.

To check for consistency in the results from the EF 3.1 method, we also calculated environmental impacts using the ReCiPe 2016 Midpoint (H) method, which confirms the energy-intensiveness of LIG production. Discrepancies between results from the two methods are negligible, with small variations due to the different characterization factors of the two LCIA methods and the coverage of substances considered in each impact category (Sect. 3 Supporting information).

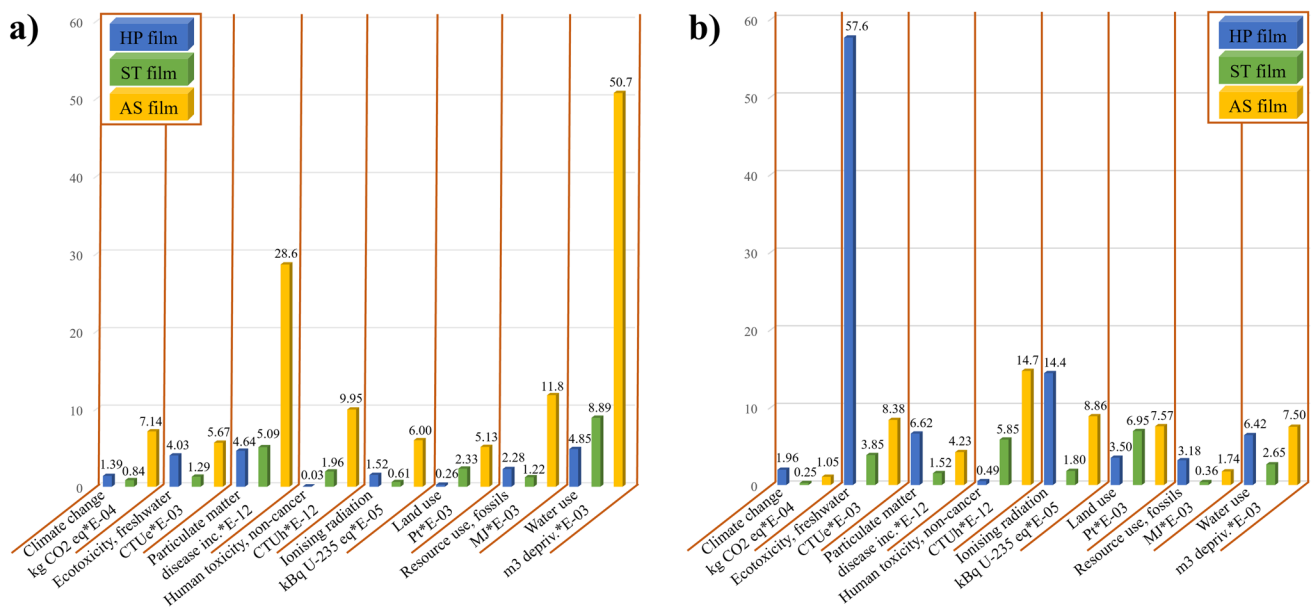


Fig. 4 Comparative LCA results of the production of **a** 1 cm² and **b** 1 g of the three unscrubbed precursors. The LCIA method used is Environmental Footprint (EF) 3.1

3.2 Comparison

3.2.1 Precursors

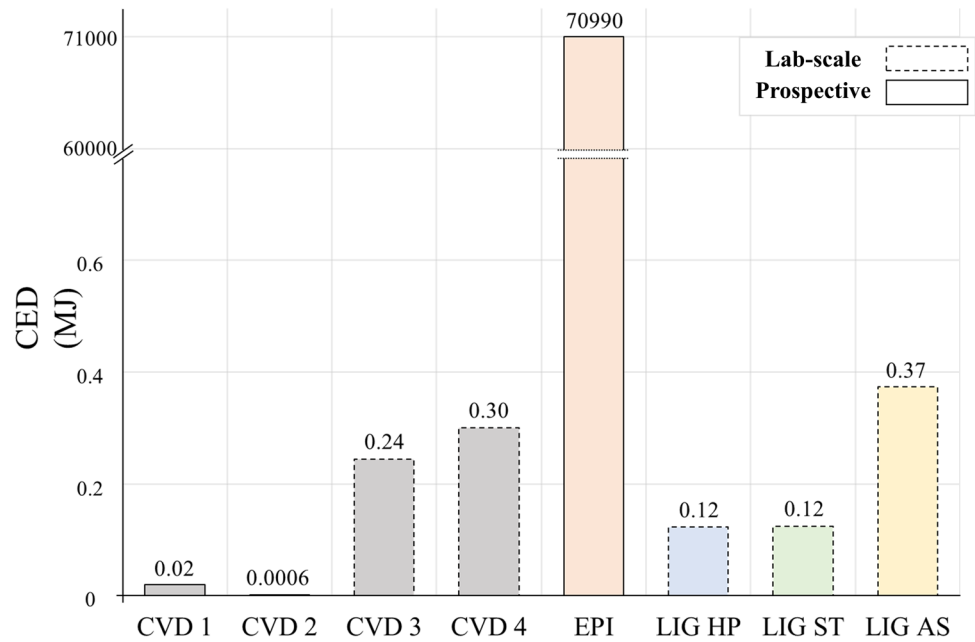
A comparison of the environmental impacts associated with the production of 1 cm² of each precursor revealed that the AS film is significantly more impactful than the others across almost all impact categories. This is because a different amount of material is necessary for each precursor to fulfill the functional unit since films have very different thicknesses. Indeed, the mass required to obtain 1 cm² of precursor was 7 mg for the HP film, 33.5 mg for the ST film, and 67.7 mg for the AS film. The heavier (and in this case, thicker) film will therefore be penalized in the evaluation of environmental impacts. To address this issue, we also evaluated the environmental impacts of precursors by choosing a mass-based functional unit (1 g). In this case, we observed a reversal of trends in more than half of the categories, where HP film has higher impacts, due to its petro-based production process. With this mass-based functional unit, ST and AS films result in lower environmental impacts, also thanks to the natural origin of the precursors. However, AS film always shows higher impacts than ST film, mostly due to the chitosan contribution. Figure 4a and b shows the comparison for the production of 1 cm² and 1 g of the three precursors, reporting a selection of the most relevant impact categories, i.e., Climate change, Freshwater ecotoxicity, Particulate

matter, Human toxicity (non-cancer), Ionizing radiation, Land use, Resource use (fossil), and Water use. The full list of impact categories is reported in Sect. 3 of Supporting Information.

This analysis opens an interesting reflection on the comparison between petroleum-derived and bio-derived materials, especially in the form of films. The three precursors exhibit significantly different thicknesses, which stem from variations in the production process and raw materials used. While HP film, which comes from an optimized industrial production process, presents high mechanical properties despite the extremely low thickness, laboratory-produced bio-derived precursors need to counterbalance their lower mechanical properties with a higher thickness to ease handling during fabrication and use.

For both bio-derived films, improved procedures could be optimized in the future, leading to reduced energy consumption and processing time, or even to the production of thinner, more homogeneous films, which can perform better both on a mechanical and environmental level (Moni et al. 2020). When considering LIG precursors, especially in the form of films, environmental impacts highly depend on the functional unit chosen; a surface-based functional unit will favor lighter precursors, independently of the nature of the material composing them. On the other hand, when considering a mass-based functional unit, bio-derived precursor may be favored.

Fig. 5 Comparison of Cumulative Energy Demand (CED) for the production of 1 cm² of graphene for several technologies: chemical vapor deposition CVD 1 (Arvidsson et al. 2016), CVD 2 (Scott and Cullen 2016), CVD 3 (Cossutta et al. 2017, 2020), CVD 4 (Cossutta et al. 2017, 2020)), epitaxial growth (EPI (Arvidsson and Molander 2017)), and laser scribing from this work (LIG-HP, LIG-ST, LIG-AS)



3.2.2 LIG

As indicated by the contribution analysis, for cradle-to-gate modeling, electricity consumption for laser scribing accounts for, on average, 90% of the environmental impacts of LIG production, regardless of the precursor nature. When comparing the three LIG production processes, it is evident that LIG produced from the AS film has the highest environmental impacts. Indeed, for AS film, the laser scribing process is repeated three times to obtain the desired quality of graphene (Table 2), which causes the tripling of energy required and thus related impacts. On the other hand, when considering LIG production from HP film and ST film, which requires about the same laser scribing time (Table 2), the choice of the precursor does not significantly affect environmental impacts. Figure 3 shows impacts associated with the production of 1 cm² of LIG from the three precursors, reporting Climate change, Freshwater ecotoxicity, Particulate matter, Human toxicity (non-cancer), Ionising radiation, Land use, Resource use (fossil), and Water use. The list of all impact categories is reported in Sect. 3 of Supporting Information.

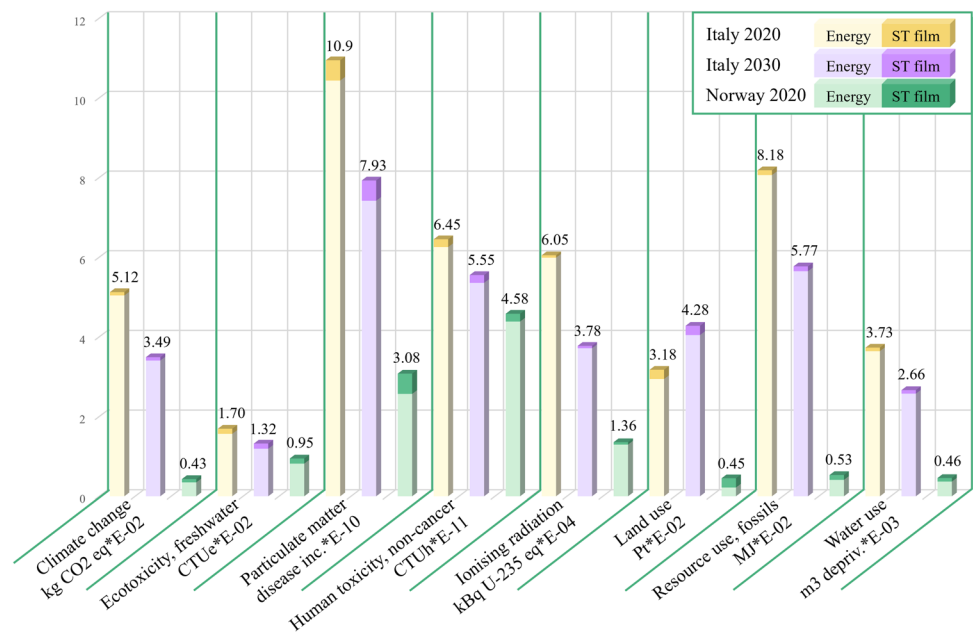
We can therefore conclude that the role of the precursor emerges only because it conditions the search for the optimal parameters of the laser scribing process. However, the bio-derived nature of the precursors does not appear to have a positive effect on the overall environmental performance. It is important to note that results could change, perhaps determining a beneficial role of bio-derived precursors compared to the petroleum-derived ones, if the entire life cycle of LIG were considered, in a cradle-to-grave perspective. Indeed, the degradation in soil of both ST film and AS

film has been experimentally tested, providing good results (Sankaran et al. 2024; Steksova et al. 2025). However, there are many possible LIG applications, which may influence the precursor choice and thus the use and end-of-life. Therefore, it would not make sense, in the current context of LIG technological development, to compare the entire life cycle of LIG deriving from such different precursors.

3.3 Comparison of LIG with other graphene production processes

From the contribution analysis and comparison between precursors, we understood the energy-intensive nature of the LIG production process and the limited role of the precursor choice on overall environmental impacts. However, we are still not able to state that laser scribing is a more environmentally sustainable technology for producing graphene. For this purpose, it is necessary to compare the environmental impacts of LIG production with those of other technologies. Therefore, we decided to compare our results with those reported and harmonized by Beloin-Saint-Pierre and Hischier (2021), using CED as an indicator. Figure 5 reports CED values that were recalculated by Beloin-Saint-Pierre and Hischier (2021), starting from previous works (with 1 cm² of graphene as the functional unit). Production technologies considered are chemical vapor deposition (CVD 1 (Arvidsson et al. 2016), CVD 2 (Scott and Cullen 2016), CVD 3 (Cossutta et al. 2017, 2020), CVD 4 (Cossutta et al. 2017, 2020)), epitaxial growth (EPI (Arvidsson and Molander 2017)), and laser scribing from this work (LIG-HP, LIG-ST, LIG-AS). When comparing the CED of the LIG production process to other graphene production

Fig. 6 Comparison of environmental impacts of the production of 1 cm² of LIG from ST film, considering alternative energy scenarios: the 2020 Italian electricity mix, the 2030 Italian energy mix, and the 2020 Norway electricity mix. The LCIA method used is Environmental Footprint (EF) 3.1



technologies, we note a difference in results whether we consider studies that model processes at the laboratory scale (named “Lab-scale” in Fig. 5), or studies that adopt prospective modeling approaches (named “Prospective” in Fig. 5). Lab-scale LCAs usually model technologies with a low level of maturity and at the current state of development, eventually using direct experimental measurements as foreground data. Prospective LCAs, instead, model product systems at a future point in time relative to the time at which the study is conducted, usually including a technological maturity increase (Arvidsson et al. 2024). In this specific case, when comparing results from LIG to those of CVD modeled at lab-scale (Cossutta et al. 2017, 2020), CED values lie within the same order of magnitude range (0.12–0.37 MJ). Conversely, when considering prospective studies (Arvidsson et al. 2016; Scott and Cullen 2016), still for CVD, CED values result much lower (<0.02 MJ). On the other hand, values from EPI are out of scale, and here, process modeling is also prospective (> 70,000 MJ) (Arvidsson and Molander 2017). These differences can be explained by considering the different temporal positioning of the various studies, which directly influences the modeling of the life cycle inventory. Graphene production technologies exhibit a wide range of TRLs, which can be explored through LCA either by projecting the future development of the technology (prospective approach) or by analyzing it in its current state of development (lab-scale approach). Even for the same technology, such as CVD, it becomes complex and potentially misleading to compare results from studies based on different technological maturity and temporal positioning. Therefore, within this context, we can limit our comparison to the lab-scale studies by Cossutta et al. (2017, 2020) (i.e.,

CVD 3 and CVD 4), wherefrom we can conclude that the LIG production process can be less energy-demanding than CVD, depending on laser scribing conditions. For the sake of completeness, it should be noted that CED results from our calculations also include the contribution of the substrates (although not extremely relevant).

3.4 Sensitivity analysis concerning alternative energy scenarios

Given the energy-intensive nature of the LIG production process, we deemed it relevant to assess its sensitivity to alternative energy scenarios. To this end, two alternative energy scenarios were analyzed: one based on the 2020 Norwegian electricity mix (from ecoinvent) and the other on a projected Italian electricity mix for 2030. When modeling the system using the Norwegian mix, which is composed of approximately 99% renewable sources, the environmental impacts of LIG production decreased by an average of 70% compared to the baseline scenario based on the Italian 2020 electricity mix (Fig. 6). This can be easily explained considering that the Norwegian electricity mix is based on 99% renewable resources, mainly hydropower (IEA 2022), leading to an important reduction of environmental impacts associated with the energy use for laser scribing. Under the Italian 2030 scenario, which reflects a realistic near-future projection with an increased share of renewables (Carvalho et al. 2022), an average impact reduction of around 20% was observed. The only impact category for which LIG production results in higher environmental impacts, compared to the baseline scenario, is land use, which is due to the higher

contribution of energy produced from photovoltaic panels in the 2030 scenario.

Overall, as the energy efficiency of the process improves, total environmental impacts decrease, making the relative contribution of the precursors more evident. Nonetheless, the ranking of the three LIGs in terms of environmental performance remains unchanged (LIG-AS < LIG-ST \approx LIG-HP). Figure 6 shows the comparison of environmental impacts associated with the production of 1 cm² of graphene from ST film in the three scenarios, as a representative case, reporting Climate change, Freshwater ecotoxicity, Particulate matter, Human toxicity (non-cancer), Ionising radiation, Land use, Resource use (fossil), and Water use. The complete impact assessment results, also for LIG prepared from the other precursors, are reported in Sect. 3 of Supporting Information.

We can therefore conclude that LIG production has the potential to be an environmentally sustainable graphene production technology, only if the energy used in all phases of the process comes from renewable sources. By doing so, environmental impacts, mainly related to the use of electricity for laser scribing, can be reduced, leading to a cleaner graphene production technology.

3.5 Methodological limitations and recommendations

Although the results discussed in the previous sections provide valuable insights into the environmental impacts of LIG production and the relative contribution of energy and material inputs, several methodological and practical limitations should be acknowledged. While specific to this study, these limitations are representative of broader challenges associated with performing cradle-to-gate LCA studies of laboratory-scale processes with low TRL (Costanzo et al. n.d.).

The first critical aspect concerns the system boundaries. The early-stage development of the LIG production process prevents the definition of downstream stages such as product use and end-of-life. As a consequence, the assessment was limited to a cradle-to-gate approach. Aspects related to feedstock availability and supply chains were not explicitly included in the environmental assessment, as they fall outside the scope of the study and would require a broader perspective. Nevertheless, polyimide and corn starch are intentionally manufactured materials, typically relying on dedicated and potentially competitive supply chains (such as electronics, food, or packaging), while almond shells represent an agricultural by-product, generated from existing food production processes and usually destined for low-value applications. At the current scale, their availability is not considered a limiting factor. However, future large-scale deployment of LIG technologies should be accompanied by a comprehensive evaluation of potential competition for

feedstocks, as this may affect both environmental and economic outcomes. Similarly, an end-of-life analysis was not conducted, as is often the case in LCAs of emerging technologies, where final applications and disposal routes have yet to be defined (Salieri et al. 2018). In the case of LIG, the wide variety of possible precursors, ranging from petroleum-derived to bio-derived materials, affects the potential final application of the produced LIG. Therefore, the research progress on the possible applications of LIG remains partly constrained by the knowledge level of the precursors. While applications of LIG from petroleum-based precursors are better documented (Zhang et al. 2023), research on bio-derived precursors is still in early development (Bressi et al. 2023). This makes it difficult to model a representative use phase or to speculate on realistic end-of-life scenarios. Additionally, the lack of comprehensive data on the biodegradability of both precursors and graphene materials limits the possibility of accounting for any environmental benefits potentially linked to this feature.

A second challenge relates to the modeling of the production system itself. Given the low TRL of the process, the system boundaries were confined within the laboratory environment, excluding elements such as upstream transport of materials and waste management operations. Although these aspects are often excluded in lab-scale LCA to avoid overshadowing the impacts of the core process, they could affect the interpretation of results, especially in terms of scalability and replicability (Beloin-Saint-Pierre and Hischier 2021). At the same time, processes at laboratory scale are rarely optimized for energy or material efficiency. This introduces a degree of uncertainty in the results, which might not reflect future improvements achievable at pilot or industrial scale. However, it is important to note that not all hotspots identified in lab-scale studies will necessarily be mitigated through scale-up and process optimization. In the case of LIG, for instance, the laser writing step is unlikely to undergo substantial technological changes, as laser scribing machines, as the one used in this study, are already commonly employed in industrial contexts. As a result, while marginal efficiency improvements may still be achievable, the energy demand associated with this process is not expected to decrease significantly at larger scales, and may even increase depending on system configuration and throughput. This reinforces the relevance of transitioning to a cleaner electricity mix as a key strategy for reducing environmental impacts. Therefore, lab-scale LCAs can still provide meaningful insights, which may eventually be complemented with prospective modeling approaches (Arvidsson et al. 2018).

Finally, a major limitation, shared with other LCA studies on nanomaterials, is the inability to account for potential environmental impacts of the graphene material beyond its production. The lack of robust ecotoxicity and human toxicity data for graphene prevents its inclusion in life cycle impact assessment (LCIA) methods, thus excluding

potentially significant impacts during the use and end-of-life phases of products containing graphene (Arvidsson et al. 2018; Bahmei et al. 2025).

These limitations do not undermine the value of the study but rather highlight important directions for forthcoming research. Future efforts should aim at expanding LCA models to cover the full life cycle of LIG-based products, eventually exploring scale-up case studies and integrating toxicity data as they become available.

4 Conclusions

Overall, LIG has emerged in recent years as a promising technology for the fast and simple fabrication of graphene, able to guarantee a high level of control over patterned structures. However, the relative simplicity of this technique and the great variety of bio-derived and waste-derived precursors that can be converted into LIG have led to declaring this technology as environmentally sustainable without presenting the results of a life cycle assessment (Claro et al. 2022; Bressi et al. 2023; Vaughan et al. 2023; Zhang et al. 2023; Moon and Ryu 2024; Silvestre et al. 2024). In other words, it was taken for granted that the possible environmental sustainability of a precursor could automatically condition the performance of the production process. In this work, the first cradle-to-gate LCA study on LIG was performed to calculate the potential environmental impacts of the LIG production process at a laboratory scale, starting from three precursors, i.e., one petroleum-derived polymer (polyimide modeled as a proxy with polyetherimide) and two bio-derived films (starch and almond shells powder/chitosan). The results showed that the hotspot of the process is the energy use for laser scribing, which contributes more than 90% for almost all impact categories, independently of the choice of the precursor, which plays a minor role in the distribution of environmental burdens. This result is particularly relevant as energy use is a contribution often misconsidered or neglected in scientific literature, at least in studies focusing on materials science and engineering and in novel technology development. Moreover, it should be noted that the laser power input in our study is based on a commercially available system widely used in industrial contexts (e.g., for cutting or engraving various materials), not on laboratory equipment. As such, the energy demand already reflects realistic industrial specifications. Therefore, while minor efficiency improvements are possible, we believe the laser's energy consumption represents a genuine and persistent hotspot, not a lab-specific artifact such as the non-optimized use of oversized ovens, solvents, or laboratory equipment. Results may change when the complete life cycle of a device is considered, including also the use phase and end-of-life. Within this context, bio-derived precursors could be adopted to make transient electronics, which provide the additional advantage of disintegrating after their operative

life, thus avoiding the environmental impacts related to the disposal or recycling process. However, two key challenges arise: first, there are currently no in-depth studies regarding the degradation of LIG in general, nor about the toxicity for humans and the environment, making it impossible to perform a complete assessment from cradle to grave. Second, different LIG applications imply different requirements, an aspect that often influences the precursor choice and the use and end-of-life phase, so it may be misleading to compare different materials for the same applications. We therefore believe that it would not make sense, in the current context of LIG technological development, to compare the entire life cycle of LIG deriving from such different precursors.

Moreover, we have also demonstrated that the environmental impact of LIG production in general, in terms of CED, can be less energy-demanding than CVD, depending on laser scribing conditions. However, this is true only when comparing lab-scale LCA studies. Comparisons with other production methods for 1 cm² of graphene proved to be unfeasible due to the incomparability between prospective and lab-scale results.

We have also assessed that it is possible to significantly reduce the environmental impacts of the LIG production process if optimized energy scenarios are considered since the highest environmental burdens are associated with energy use for laser scribing. When improving energy efficiency, the relative contribution of precursors emerges; however, the precursor's role should be further investigated, eventually considering cradle-to-grave modeling.

In conclusion, we believe that extreme care should be taken when talking about the environmental sustainability of the LIG production process. We hope that this work can be useful for the advancement of the TRL of LIG production, which in the future should focus on the optimization of energy consumption during the scribing process, to actually achieve the so-claimed cleaner graphene production technology.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-025-02524-w>.

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Data availability The authors confirm that all data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no competing interests.

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