



Cite this: DOI: 10.1039/d6gc03362h

Life cycle assessment of electrochemical double-layer capacitors using bio-waste-based electrodes

Fatemeh Bahmei,^a Sebastian Pinto Bautista,^a María Arnaiz,^c Jon Ajuria^c and Marcel Weil^{a,b}

Bio-waste-derived activated carbon (AC) is a promising electrode material for sustainable electrochemical double-layer capacitors (EDLCs), yet its environmental performance remains insufficiently quantified, particularly at the full-cell level. This study evaluates the sustainability of a prototype EDLC using AC derived from olive pits through a cradle-to-gate life cycle assessment (LCA). The assessment covers AC production, electrode fabrication, and cell assembly, combining primary laboratory-scale data with literature inventories and background databases. Environmental impacts were quantified using the Environmental Footprint 3.1 method, with functional units of 1 kg AC and, for the 34 F pouch-cell EDLC, 1 F of capacitance and 1 Wh of discharge energy. Results show that laboratory-scale AC production is highly energy-intensive, with thermal treatment as the dominant hotspot, resulting in a global warming potential (GWP) of 441.5 kg CO₂-eq per kg AC. At the device level, electrode manufacturing dominates the environmental profile, mainly due to AC production, drying, calendaring, and cell assembly. In the baseline case, EDLC impacts are strongly shaped by the laboratory-scale dataset. Scenario analysis reveals a pronounced scale effect. When higher-scale AC production inventories substitute the laboratory dataset, overall EDLC production impacts decrease by over 80% with respect to the baseline. In these scenarios, GWP converges to approximately 5.6×10^{-3} – 5.8×10^{-3} kg CO₂-eq per F, and hotspots shift to electrode processing, assembly energy, and electrolyte supply. Overall, olive-pit-derived AC is a promising sustainable precursor for EDLCs; however, its advantage depends on efficient processing and large-scale production. This study provides a robust basis for sustainable bio-waste-based supercapacitor design.

Received 8th June 2026,
Accepted 8th September 2026

DOI: 10.1039/d6gc03362h

rsc.li/greenchem

Green foundation

1. This work advances green chemistry by assessing a full electrochemical double-layer capacitor (EDLC) using activated carbon derived from olive pits as the electrode material. The cradle-to-gate LCA links bio-waste valorization, activated-carbon synthesis, electrode fabrication, and multilayer pouch-cell assembly, addressing the current lack of device-level environmental evidence for bio-derived EDLCs.
2. Using primary laboratory-scale manufacturing data, the study identifies thermal treatment during olive-pit activated-carbon production as the dominant hotspot, with a global warming potential of 319.6 kg CO₂-eq per kg AC. At the EDLC level, the baseline impact is mainly driven by electrode manufacturing, including AC production, drying, calendaring, and cell assembly.
3. Scenario analysis shows that replacing the laboratory-scale AC inventory with literature-based higher-scale AC production datasets reduces total EDLC production impacts by more than 50% and shifts the main hotspots toward electrode processing, assembly energy, and electrolyte supply. Future optimization should focus on higher-throughput AC production, improved thermal efficiency, reagent recovery, renewable electricity, and more representative electrolyte modeling.

1. Introduction

Electrochemical double layer capacitors (EDLCs), commonly referred to as supercapacitors, have emerged as an essential energy storage technology, serving as a bridge between conventional capacitors and batteries.¹ Unlike Lithium-ion batteries (LIBs), which are limited by slower charge-discharge kinetics, EDLCs offer exceptional power density, rapid charge/discharge capabilities, and exceptional durability,² making them ideal for applications requiring high-intensity, short-duration

^aHelmholtz-Institute for Electrochemical Energy Storage (HIU), KIT, Ulm, Germany.
E-mail: fatemeh.bahmei@kit.edu, sebastian.bautista@kit.edu

^bInstitute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

^cCentre for Cooperative Research on Alternative Energies (CIC energiGUNE), Basque Research and Technology Alliance (BRTA), Alava Technology Park, C/Albert Einstein 48, 01510 Vitoria-Gasteiz, Spain

energy bursts.³ Due to their long-term stability, they own remarkable cycle life and robustness making them critical components in diverse applications, such as emergency power backups, regenerative braking in electric vehicles, and power stabilization in industrial systems.⁴

Supercapacitors are classified into three main categories according to their energy-storage mechanisms: electric double-layer capacitors, pseudocapacitors, and hybrid capacitors. Among these, EDLCs are particularly attractive because of their high-power density, rapid response, and long cycle life. Activated carbon (AC), a key electrode material in EDLCs, owes its effectiveness to its high specific surface area and well-developed pore structure.⁵ Moreover, the use of abundant, high-performance materials such as AC enhances the scalability and commercial viability of EDLCs.⁶ Its properties depend largely on the precursor type, which can include fossil-based sources, synthetic polymers, carbon-rich waste, animal biomass, micro-organisms, and plant-derived materials.^{7,8} Among these, plant-based biomass is particularly attractive due to its renewability, abundance, potentially regional sourcing or waste utilization to produce more sustainable supercapacitor.⁹

However, even when biomass materials are used to produce activated carbon, the resulting product is not necessarily fully sustainable due to energy-intensive carbonization and chemical activating agents. Comprehensive quantitative environmental assessments, such as Life Cycle Assessment (LCA), are then critical for evaluating its sustainability¹⁰ and important to identify optimization potentials for this emerging energy storage technology.

While numerous studies have assessed the environmental impacts of AC production from various precursors, only a limited number specifically focused on the use of AC in supercapacitors within a LCA framework. When narrowing the scope to studies that both evaluate AC for EDLC applications and apply LCA, the literature becomes notably sparse. Only six studies have adopted a cradle-to-gate system boundary to quantify the environmental impacts associated with producing AC intended for use in supercapacitors.^{11–16}

However, these studies overlook downstream processes like electrode fabrication, cell assembly, and device-level performance, limiting the understanding of trade-offs between electrochemical performance and environmental impacts. To address this, our study conducts a comprehensive LCA of a prototype EDLC, encompassing all components from raw material extraction to cell assembly and performance evaluation, providing critical insights for sustainable design and material development or selection.

2. Literature review on the sustainability of AC and EDLCs

Activated carbon derived from biomass is a promising material for sustainable energy storage systems due to the wide availability of renewable precursors.¹⁷ The olive oil industry generates substantial residual streams, primarily comprising two distinct streams: olive pits (stones) and olive pomace, a semi-

solid residue of pulp, skin, and fragmented stones. Terminology varies across the literature, where these streams are described as “waste”, “residue”, or “by-product” depending on context.^{17–20} This distinction can affect LCA allocation choices and whether upstream burdens are attributed to olive pits. In this study, olive pits are modeled as a low-value residue entering the system without upstream burdens.

The Mediterranean region, a key producer, generates over 3 million tons of olive oil annually, resulting in more than 4 million tons of olive pits alone. In modern milling processes, a destoning step is often employed where the crushed olive paste is passed through a separator, yielding a distinct and easily collectible stream of olive pits, while the remaining pulp proceeds to centrifugation.^{18,20} Currently, much of this resource is underutilized in low-efficiency combustion for energy.¹⁹ However, according to the European waste hierarchy (Directive 2018/851), material recovery should be prioritized over thermal recovery.¹⁹ The substantial annual generation of olive pits waste, combined with its high carbon content, makes it an excellent candidate for conversion into value-added porous carbons.

Studies have explored both physical and chemical activation methods for olive pits-derived AC, demonstrating its potential for EDLC electrodes.^{21–26} Other feedstocks, including corn stover, oil palm leaves, *Sesbania*, and filter cake, have also been investigated for their high specific surface area and electrochemical performance.^{11,27}

Life cycle assessment studies consistently identify activating reagents (*e.g.*, KOH, H₃PO₄, ZnCl₂) and thermal energy demand as major contributors to environmental impacts. Zhang *et al.*²⁷ reported GWP values of ~15.4–65.9 kg CO₂-eq per kg for corn-stover AC across eight lab-scale process variants, with burdens driven by the quantities and types of activating reagents and other energy-intensive steps. Amin *et al.*²⁸ documented 5.21 kg CO₂-eq per kg and ~70.5 MJ kg^{−1} for AC from olive-pruning residues and *Lantana camara* using a pilot-scale activation furnace, with hotspots linked to H₃PO₄ use, electricity consumption, and eutrophication/toxicity effects. Studies on woody biomass, reactivated coal, and sewage sludge show the same trend. Whether the data come from pilot-scale,²⁹ industrial-scale production,³⁰ or lab-scale pyrolysis,^{20,28} the main environmental impacts come from the activating reagents (KOH, H₃PO₄, ZnCl₂) and the carbonization or heating steps (Table 1).

Building on these material-level studies, recent work has begun to link electrochemical performance of ACs with environmental outcomes, showing how material properties influence sustainability. For example, Luanwuthi *et al.*¹¹ demonstrated that high-capacitance ACs (*e.g.*, oil-palm-leaf AC, 237.6 F g^{−1}; 12.1 kg CO₂-eq per kg) substantially lower normalized impacts compared to low-performing materials such as filter-cake-derived AC (7.3 F g^{−1}; 11.5 kg CO₂-eq per kg). Similarly, Petri *et al.*¹³ showed that KHCO₃ recovery and energy integration can reduce GWP by up to 75% for lignin-rich biodigester-waste-derived AC. Wang *et al.*¹⁴ also highlighted the importance of reagent (KOH reuse *vs.* virgin KOH) in shaping both environmental and economic feasibility of AC for supercapacitor electrodes. Zhang *et al.*¹⁶ further demonstrated that

Table 1 Summary of LCA studies on activated carbon

Study	Feedstock	System boundary	Functional unit	Scenario description	GWP (kg CO ₂ -eq)	Scale type	Application focus	Sensitivity analysis
Weil <i>et al.</i> ¹⁵	Coconut shells and palm-oil shells	Gate-to-gate	1 kg of carbon-based material	Comparison of different carbon-based materials for electrode production	—	Prospective analysis	Supercapacitors	No
Hjaila <i>et al.</i> ³³	Exhausted olive-waste cake	Gate-to-gate	1 kg AC	Chemical activation using H ₃ PO ₄ ; impacts analyzed per process step	11.10	Lab scale	No application tested (LCA of production only)	Yes (energy recovery from pyrolysis gas, H ₃ PO ₄ recovery/reuse, residue disposal/recycling, and lab-to-industrial scale effect)
Arena <i>et al.</i> ³⁴	Coconut shells	Cradle-to-gate	1 ton of AC	Physical activation (steam) of coconut-shell char; comparison of base case vs. 4 alternative scenarios (e.g., shells used as biofuel, distillate release, relocation to NZ, renewable electricity)	≈10.4 kg CO ₂ -eq per kg AC (base case; 80% reduction possible with renewable power)	Industrial (commercial data from producers)	No application tested (LCA of production only)	Yes (±10% electricity & feedstock use; 4 scenario analyses on energy source & emissions management)
Gu <i>et al.</i> ²⁹	Woody biomass	Cradle-to-gate	1 kg of AC	Comparison of biochar-based AC vs. coal-based AC using rotary calciner	Biochar AC: 8.60; coal AC: 18.28	Pilot/industrial scale	No application tested (LCA of production only)	No
Heidari <i>et al.</i> ³⁵	Eucalyptus wood waste	Gate-to-gate	1 kg of product (bio-oil or AC)	Comparison of fast pyrolysis (bio-oil) and slow pyrolysis (AC) using two activating agents (ZnCl ₂ and H ₂ PO ₄)	Bio-oil: 1.45; AC-ZnCl ₂ : 8.58 kg; AC-H ₃ PO ₄ : 5.58	Lab scale	No application tested (LCA of production only)	Yes (±20% change in electricity, activating agent, and N ₂ flow rate)
Loya-González <i>et al.</i> ³⁶	Corn pericarp	Cradle-to-gate	1 kg of AC	Multiojective optimization with/without chemical activator	Single score: as low as 0.06–0.09 Pt kg ^{−1} (not in CO ₂ -eq, but includes climate impact under ReCiPe 2008)	Lab scale	Waste water treatment	Yes (weights assigned to yield, adsorption capacity, and single score in the desirability optimization).
Cossutta <i>et al.</i> ³¹	Not disclosed – modeled using GaBi synthetic activated carbon dataset	Gate-to-grave	One rack of 5 supercapacitors (5 F each), providing energy for 4 mirror movements in 20 s	Comparison of graphene vs. activated carbon supercapacitors under current, advanced performance, and renewable electricity scenarios	Graphene supercapacitors ~0.211, about 2.5 times higher than AC supercapacitors (~0.085) per 5-unit rack	Prospective industrial scale (simulation based on lab data)	Supercapacitors	Yes Material performance (e.g., graphene reaching theoretical specific capacitance) Electricity mix (EU mix vs. renewable energy) Recycling effects No
Tiegam <i>et al.</i> ³⁷	Cocoa pods	Cradle-to-gate	4 gr of AC	AC production from cocoa pods using KOH	4.63	Lab scale	No application tested (LCA of production only)	No
Vilén <i>et al.</i> ³⁰	Coal, coconut shell, wood, peat, reactivated coal	Cradle-to-gate	1 kg of AC	Comparison of AC from different raw materials including reactivated AC	Reactivated coal: ~1.5–2; coconut shell/wood: ~2.6; coal: ~7–10 AC: 1.5–1.7	Simulation and literature data	No application tested (LCA of production only)	Yes (electricity, chemicals)
Huang <i>et al.</i> ³⁸	Sewage sludge	Cradle-to-gate	1000 kg of dried sludge	Slow/fast pyrolysis with gas recovery, various residence times		Simulation (based on pilot data)	No application tested (LCA of production only)	Yes (reagent, process yield, and product market value)

Table 1 (Contd.)

Study	Feedstock	System boundary	Functional unit	Scenario description	GWP (kg CO ₂ -eq)	Scale type	Application focus	Sensitivity analysis
Wang <i>et al.</i> ¹⁴	Lignocellulosic biomass	Cradle-to-gate	1000 kg of AC	Comparison of AC production as an electrode material	6.28 × 10 ⁴	Industrial	Supercapacitors	Yes (recycling of KOH and use of Steam activation)
Zhang <i>et al.</i> ¹⁶	Floc sludge	Cradle-to-gate	1 g of floc sludge for porous carbon electrodes	Conversion of 1 g floc sludge into porous carbon electrodes <i>via</i> acid treatment and KOH activation for supercapacitors	—	Lab-scale	Supercapacitors	No
Shaheen <i>et al.</i> ³⁹	Date palm waste, woody biomass	Gate-to-gate	1 kg of product	Comparison of biochar <i>vs.</i> AC performance and impact	Biochar: 1.53; AC: 8.96	Simulation (with lab data)	Waste water treatment	Yes (transportation distance and energy)
Amin <i>et al.</i> ²⁸	Olive tree, Lantana camara	Gate-to-gate	1 g of AC	H ₃ PO ₄ chemical activation of olive tree and Lantana camara	AC from olive tree: 5.21	Lab scale	No application tested (LCA of production only)	No
Chaparro-Garnica <i>et al.</i> ⁴⁰	Hemp residues and almond shells	Cradle-to-gate	0.4 g AC + 0.066 g levulinic acid	Reference (lab-scale baseline), Max Lab (equipment at full capacity), and Improved (optimized durations, reduced washing, upscaling assumptions)	4.9	Lab scale	No application tested (LCA of production only)	Yes (three scenarios compared: energy use, pyridine input, scale-up efficiency); electricity and pyridine identified as key impact drivers
Jiunn Boon Yong <i>et al.</i> ⁴¹	Oil palm biomass and bituminous coal	Cradle-to-gate	1 kg activated carbon	Five routes: biomass-based (R1 = pyrolysis + physical, R2 = pyrolysis + chemical, R3 = gasification + physical, R4 = gasification + chemical) <i>vs.</i> coal-based (R5)	Biomass AC: 0.77–3.22; coal AC: 8.6 kg	Industrial (modeled from literature data)	No application tested (LCA of production only)	No
Amin <i>et al.</i> ⁴²	Quercus alba (oak wood)	Gate-to-gate	1 g of AC	Comparing four activators (H ₃ PO ₄ , KOH, FeCl ₃ , ZnCl ₂)	H ₃ PO ₄ : 2.90; KOH: 2.63; FeCl ₃ : 2.01; ZnCl ₂ : 3.12	Lab scale	No application tested (LCA of production only)	No
Pereira <i>et al.</i> ¹³	Banana peel	Cradle-to-gate	1 kg of activated biochar	NaOH activation followed by pyrolysis at 600 °C, assessed for dye removal	137.76	Prospective analysis	Waste water treatment	Yes (activation agents)
Petri <i>et al.</i> ¹³	Lignin-rich waste of a biodigester plant	Cradle-to-gate	1 kg of AC	AC production from lignin-rich biodigester <i>via</i> pyrolysis and KHCO ₃ activation	63.3	Lab -scale	Supercapacitors	Yes (energy recovery, KHCO ₃ and ethanol recovery scenarios)
Luanwuthi, Akkharaamnuay <i>et al.</i> ¹¹	Oil palm leaves, Sesbania, and filter cake	Cradle-to-gate	1 kg of AC and 1 F of electrode	Comparison of AC production from three biomass sources as us electrode material	11.5–13.3 per kg of AC; 4.43 × 10 ^{−3} –2.34 × 10 ^{−2} per F of electrode	Lab-scale	Supercapacitors	Yes (focus on wastewater generation and electricity consumption during hydrothermal carbonization)
Luanwuthi, Iamprasertkun <i>et al.</i> ¹²	Oil palm leaves	Cradle-to-gate	Per ton of AC	Comparison of different production scales	9.49 tons CO ₂ -eq per ton of AC	Use the experimental data to simulate three different production scales	Supercapacitors	Yes (AC price, raw material costs, utility costs, tax rates, plant capacity, and operating hours)

Table 1 (Contd.)

Study	Feedstock	System boundary	Functional unit	Scenario description	GWP (kg CO ₂ -eq)	Scale type	Application focus	Sensitivity analysis
Zhang <i>et al.</i> ²⁷	Corn stover	Cradle-to-gate	1 kg of AC	Eight AC production methods with various activators and energy sources	15.4–65.8	Lab scale	No application tested (LCA of production only)	Yes (electricity and activators)
Amin <i>et al.</i> ⁴⁴	Fiddlewood and Jacaranda leaves	Gate-to-gate	1 kg activated carbon	Four production routes: R1 = pyrolysis + physical; R2 = pyrolysis + chemical (H ₃ PO ₄); R3 = gasification + physical; R4 = gasification + chemical	R1 = 1.08; R2 = 2.81; R3 = 0.77; R4 = 3.22	Lab scale	No application tested (LCA of production only)	No
Saleem <i>et al.</i> ⁴⁵	Coconut shells	Cradle-to-gate	1 kg AC and 1 kg dye adsorbed	kg dye adsorbed; two activation routes: KOH vs. NaOH (2 M). Evaluated both mass-based and performance-based FUs. Compared with commercial AC	KOH: 1.255; NaOH: 1.210	Lab scale	Waste water treatment	Yes (tested molarity (1–3 M), sunlight vs. oven drying; $\pm 7.5\%$ energy and $\pm 7.7\%$ GWP changes)

processing choices, particularly the pretreatment route (*e.g.*, different acids) and the KOH/C activation ratio, strongly affect pore development and therefore influence both electrochemical performance and environmental impacts.

However, substantial gaps persist in literature when moving from activated carbon production to full EDLC systems. A primary limitation is the common “cradle-to-gate” scope focused solely on AC production, which overlooks critical components such as electrode fabrication, cell assembly, and end-of-life management. This narrow scope limits the relevance of such studies for drawing conclusions at the cell level. Furthermore, a significant disconnect exists between electrochemical analysis and LCA while most studies report performance using three-electrode configurations, which primarily characterize a single working electrode against reference/counter electrodes rather than a complete two-electrode EDLC device. Even in those cases, a comprehensive environmental assessment of cell-level components, such as separators, electrolyte, current collectors, and packaging, is usually missing.

This gap is made larger by the fact that electrochemical performance is rarely linked to LCA. Functional units that reflect performance, such as impacts per farad, are still uncommon. The existing body of supercapacitor-related LCA is also fragmented. Some studies assess AC production in isolation from capacitor performance, while others evaluate supercapacitor behavior using industrial AC datasets that are not representative of bio-based precursors. Additionally, most available data originates from laboratory-scale processes, with limited consideration of scale-up effects, energy integration, or the recovery of solvents and alkalis. At the device level, comparative LCAs of active materials further indicate that electrochemical behavior can strongly influence results. Cossutta *et al.*³¹ found that graphene's low specific capacitance increases cradle-to-grave GWP relative to activated carbon, whereas prospective improvements in capacitance reverse this trend. Crucially, apart from the study by Kamali *et al.*,³² which focuses on electrolytes, no published work offers a complete LCA of an EDLC based on bio-derived AC that systematically links production conditions, electrochemical performance, and full cell-level behaviour.

These gaps motivate the present comprehensive LCA of an EDLC, which spans raw material extraction to cell assembly, and incorporates performance-normalized metrics. This includes a systematic examination of how precursor choice, activation route, material properties, and process design influence environmental impacts and opportunities for improvement.

3. Materials and EDLC cell manufacturing

3.1 Activated carbon production

In order to prepare the AC material, crushed olive pits were loaded in a stainless-steel tubular furnace for the pyrolysis process by heating up under an argon flow of 100 ml min^{−1} at a ramp rate of 5 °C min^{−1} to a pre-defined temperature of 700 °C

and further holding it for 2 h. For one complete pyrolysis batch, 20.4 g of crushed olive pits produced 5.39 g of hard carbon, corresponding to a carbonization yield of 26.4%. The obtained carbon was then physically mixed with KOH at a C/KOH mass ratio of 1 : 6 and placed in an Inconel® boat in order to activate it by heating up under an argon flow (100 ml min⁻¹) inside a horizontal stainless-steel tube within a tubular furnace. The heating ramp rate was 5 °C min⁻¹ and the holding time at 700 °C was 2 h. After activation, the microporous AC was washed off with a diluted solution of hydrochloric acid and water until neutral pH was reached and then it was dried at 120 °C under vacuum.^{26,46} In the measured activation experiment, 1.99 g of hard carbon produced 1.26 g of final dried AC after activation, washing, and drying, corresponding to an activation yield of 63.3%. Based on the carbonization and activation yields, the overall olive-pit-to-AC yield was approximately 16.7%.

3.2 EDLC production

All electrode preparation, drying, and EDLC pouch cell assembly were performed in an ISO Class 7 controlled dry room, maintained at an average dew point of -60 °C, a temperature of 21 °C, and an overpressure of 30 Pa. Slurries were produced using a disperser-homogenizer (Dissolver DISPERMAT, VMA Getzmann). In detail, PVDF binder was first dissolved in NMP by stirring at 500 rpm for one hour. Conductive additive and activated carbon were then gradually incorporated into the binder solution, with each addition stirred at 2000 rpm for two hours to achieve a uniform slurry. The coating process was performed in a roll-to-roll coating line from B&W Megtec. The dried laminates were subsequently calendered using a roll press (Mediatech, Republic of Korea).^{6,26}

Pouch cells were assembled using three double-sided positive electrodes and two double-sided plus two single-sided negative electrodes, with an AC mass loading of approximately 7.2 ± 0.1 mg cm⁻² in each layer. All electrodes were ~20 cm² size and cells were assembled by the Z-holding technique with cellulose separator (Table 2).⁶

3.3 EDLC characterization

Electrochemical characterization was carried out in a VMP3 Biologic potentiostat. The latter are based on galvanostatic charge/discharges (GCPL) at different currents from 0.1 to 10 A. The specific capacitance (eqn (I)), energy density (eqn (II)), and power density (eqn (III)), values from electrochemical measurement are obtained with the following equations,

$$C_{\text{cell}}(\text{F g}^{-1}) = \frac{I \cdot \Delta t}{2m_e \cdot \Delta V} \quad (\text{I})$$

$$E(\text{Wh g}^{-1}) = \frac{1}{2} C_{\text{cell}} (V_{\text{max}}^2 - V_{\text{min}}^2) \quad (\text{II})$$

$$P(\text{W g}^{-1}) = \frac{E}{\Delta t} \quad (\text{III})$$

where C_{cell} is cell capacitance, I current, Δt discharge time, m mass, ΔV cell voltage, V_{max} upper voltage, V_{min} lowest voltage, E energy and P power.

Table 2 Composition of the EDLC

Component	Details
Positive electrode	3 double side layers Aluminum current collector Olive pits derived AC as active material Formulation (wt%): 90% AC, 5% C65, 5% PVdF
Negative electrode	2 double side layers/2 single side layers Aluminum current collector Olive pits derived AC as active material Formulation (wt%): 90% AC, 5% C65, 5% PVdF
Pouch	Multilayer pouch Casing of aluminum and polyethylene (PE)
Electrolyte	1 M Et ₄ NBF ₄ (acetonitrile)
Electrode tabs	Aluminum size: 0.7 cm × 3.5 cm × 100 μm. Polypropylene (PP9 size: 1.1 cm × 0.8 cm × 100 μm)
Separator	Cellulose based, 30 μm thickness

4. Life cycle assessment

To assess the environmental profile of producing a complete EDLC device based on AC derived from olive pits, a cradle-to-gate LCA was conducted in accordance with the ISO 14040/14044 standards.¹⁰ The study was structured into four distinct phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

The goal and scope definition phase established the study's boundaries and objectives, ensuring alignment with stakeholder expectations. In the LCI phase, comprehensive data on all relevant inputs and outputs, including raw materials, energy consumption, and emissions, were collected and compiled. Mass and energy balances were subsequently performed to quantify the material and energy flows associated with the production process. The LCIA phase then translated these inventory results into environmental impact categories using standardized life cycle impact assessment methodologies.¹⁰

4.1 Goal and scope definition

The primary objective of this study is to characterize the environmental profile of the processes and pre-chain involved in the manufacturing of an EDLC test-cell with activated carbon from olive pits as active material. This analysis shall enable the identification of potential environmental hotspots and of mitigation strategies to support the further development of the technology.

The LCA is divided into two distinct parts. The first part focuses on assessing the environmental impacts associated with the production of AC derived from olive pits. The functional unit (FU) for this assessment is the production of 1 kg of AC. It must be noted that, because olive pits are a by-product of olive oil extraction, it is herein assumed that they enter the AC production system boundaries free of environmental burdens.

The second part of the study focuses on the production of an EDLC test-cell with AC as the active material in the electrodes. The EDLC assessment was conducted using three functional units: the production of one complete 34 F test cell, the

production of an EDLC providing 1 F of capacitance, and the production of an EDLC providing 1 Wh of discharge energy under the reported test conditions. The material and energy inventory of the experimentally produced cell was first quantified per cell and subsequently normalized to 1 F and 1 Wh based on the measured cell capacitance and discharge energy, respectively. The system boundaries for both AC and EDLC production are defined as cradle-to-gate, encompassing all processes from raw material extraction to the final manufacturing step. The potential effects of the use-phase and end-of-life stages are excluded from this assessment. Fig. 1 illustrates the system boundaries defined in this study and the step sequences followed in the production of AC and the EDLC.

4.2 Life cycle inventory (LCI)

The foreground systems were modeled using mostly primary data of laboratory-level AC and EDLC prototype production, collected in cooperation with CIC energiGUNE through laboratory measurements and experimentally reported process data, supplemented by calculated and estimated inventory flows. The measured or experimentally reported data included the masses of solid and liquid inputs and outputs, process temperatures, heating rates, holding times, and gas flow rates. In contrast, the electricity consumption of the equipment used for AC production was not directly measured using an electricity meter and was therefore estimated based on equipment power and operating time. For the grinding step, electricity consumption was estimated using the rated power of the grinder and its operating duration. For primary pyrolysis and activation, the furnace electricity demand was calculated separately for the heating and holding stages. During heating from 25 to 700 °C, the power was assumed to increase linearly, and 50% of the reported furnace power was used as the

average power. The full reported power was applied during the two-hour holding period, while no electricity was allocated to cooling because the furnace was switched off. This resulted in an estimated electricity demand of 1.25 kWh per furnace cycle. The energy required for final drying was estimated from the measured water loss, considering the sensible heat required to heat the water and its latent heat of evaporation. A thermal efficiency of 60% was assumed. Full equipment capacity was considered when scaling the material throughput and allocating electricity to one batch. However, this assumption refers to equipment loading and does not imply that the actual electricity consumption was directly measured. Because these electricity values were estimated rather than metered, they may differ from the actual operating electricity demand. Detailed calculation procedures, equations, equipment specifications, and assumptions are provided in Tables S1–S5 of the SI.

Additional literature sources were used to complement missing inventories of the foreground system, specifically the electrode tabs,⁴⁷ the cellulose separator,⁴⁸ and production of activated carbon at different scales. The background system, which covers the upstream pre-chains of AC and supercapacitor components, was modeled using secondary data from the commercial ecoinvent 3.12 database. Regarding electricity mix, because production of AC and EDLC takes place in mainland Europe, the European ENTSO-E mix has been used in our model. The complete set of inventories can be found in the SI (Tables S1 to S22).

Regarding EDLC production, the energy demand for cell assembly was estimated using pilot-scale LIB pouch-cell manufacturing data from Thomitzek *et al.*⁴⁹ The considered operations comprised electrode-stack packaging, contacting, pouch deep drawing, housing, electrolyte filling and closing. The corresponding process-specific values were summed, resulting

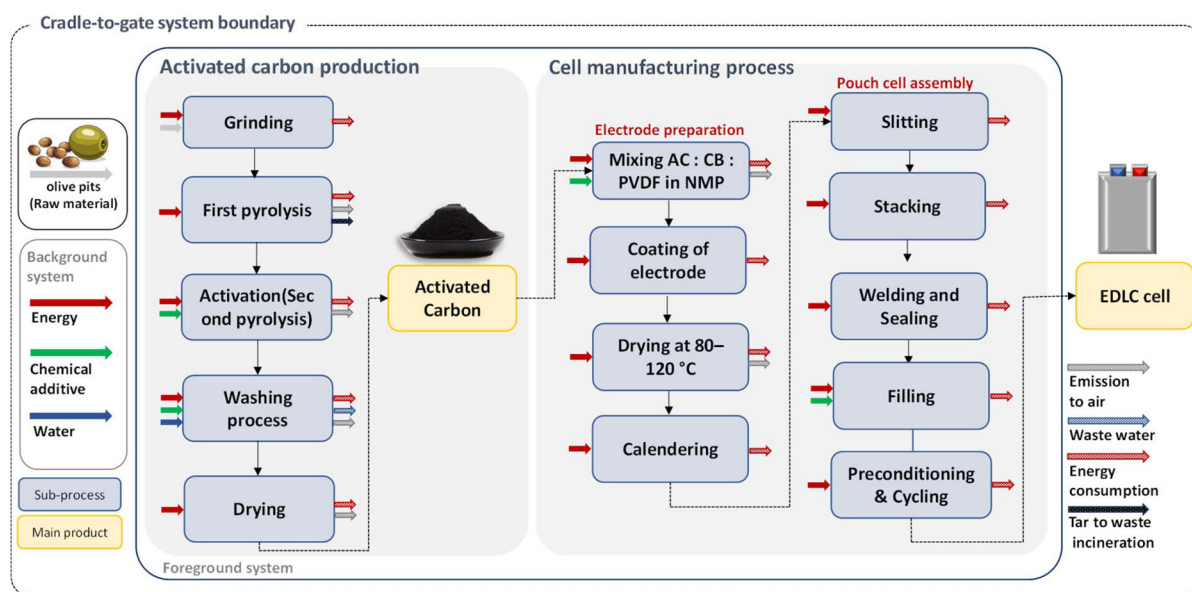


Fig. 1 System boundaries for the LCA.

in an assembly energy demand of 0.352 kWh per cell. Dry-room conditioning and post-assembly aging were not included in these estimates. The energy demand for electrode processing was estimated from the amount of NMP contained in the applied slurry derived from the cell composition described in section 3.2. Based on a slurry composition of 40.53 wt% solids and 59.47 wt% NMP, the production of the complete electrode stack required approximately 2.70 g of NMP. An energy intensity of 10 kWh per kg of evaporated and recovered NMP was adopted from Ahmed *et al.*,⁵⁰ resulting in 0.027 kWh per stack for primary drying and solvent recovery. This value was multiplied by a factor of 1.22, derived from the process contributions reported by Degen,⁵¹ to account for slurry mixing, calendaring, slitting and final electrode drying. After applying a process yield of 95% to account for potential losses, the total energy demand for electrode processing was estimated at 0.035 kWh per complete electrode stack, distributed proportionally among the double-sided and single-sided electrode layers.

4.3 Life cycle impact assessment

The impact assessment method used in this assessment is the Environmental Footprint EF V3.1, which has been implemented in the software OpenLCA 2.5 from GreenDelta. This method has been developed by the Joint Research Centre (JRC) of the European Commission and is officially endorsed under the Product Environmental Footprint (PEF) framework.⁵² In the following, a detailed analysis of four impact categories is provided. These categories are: 'acidification' [mole H⁺], reflecting potential damage to soil and water associated primarily to sulfur compound emissions; 'climate change' [kg CO₂-eq], related to the increase in global average temperature due to greenhouse gas emissions; 'resource use' (kg Sb-Eq), related to the depletion of metals and minerals; and 'particulate matter' [disease incidence], capturing the negative impacts on human health caused by emissions of particulate matter during the life cycle of a product. The complete set of results, including all 25 categories of the EF method, can be found in the SI (Tables S23 to S27).

4.4 Limitations

The main limitation in this study is related to the technology readiness level (TRL) of the emerging system. Because the olive-pits-derived AC production route and the bio-derived AC-based EDLC configuration are currently developed and tested at laboratory scale, we assume a TRL of ~3 for the AC production route and ~5 for the EDLC prototype concept. This low-to-intermediate TRL implies that available primary data are largely limited to laboratory and pre-pilot, small-batch production conditions and have not yet been validated under pilot-line or industrial operating conditions (*e.g.*, yields, throughput, and energy demand per unit output), which hinders robust modeling of the use phase and end-of-life of the assessed EDLC configuration. While the current focus is on the production phase, excluding other life cycle stages could lead to a skewed picture of the environmental profile of

the systems studied. Moreover, laboratory-scale production is typically associated with overestimation of material and energy demand, which distorts the results and limits their interpretation. The hypothetical scale-up scenarios also introduce uncertainty because literature-based AC production inventories were substituted while the electrochemical performance of the olive-pit-derived AC was retained, as discussed in section 5.3. Additionally, the potential effects of infrastructure and transportation necessary for the production of AC and EDLC have been neglected. As the technology evolves into higher TRL, a comprehensive sustainability assessment should include these effects to enable a robust understanding of the potential effects of technology development. Regarding methodological aspects, the allocation strategy of assuming burden-free olive pits can be a subject of discussion. This decision is based on the assumption that olive pits are considered a low-value residue disposed of or treated as biomass for energy recovery.²⁰ Under this premise, only the burdens of its transportation and preparation would be considered within the system boundaries, but because a specific supply chain of olive pits has not been defined, the latter has also been neglected. Further research should focus on the influence of transportation and distribution of future AC production facilities.

Another limitation is found in the analysis of pilot-scale EDLC production. Here, the datasets for AC production from olive-waste cake reported by Hjalila *et al.*³³ and from coconut shells reported by Arena *et al.*³⁴ were used as proxies for small- and large-pilot-scale production, respectively. These scenarios are hypothetical and are not intended to imply that different feedstocks would result in identical electrochemical performance. Rather, they illustrate the potential effects of scaling up AC production while assuming that the feedstock and electrochemical properties of the laboratory-scale system are retained. Because primary scale-up data were unavailable, the literature values were used solely as proxies for energy demand. This assumption introduces uncertainty, as different feedstocks may require different processing conditions, and is therefore acknowledged as a limitation of the analysis. Moreover, due to the lack of process-specific energy data for pilot-scale EDLC production, the energy demand associated with cell manufacturing was estimated using pilot-scale data from LIB manufacturing studies. These values were applied as proxies, and their uncertain transferability to the investigated EDLC system limits the interpretation of the results.

5 Results and discussion

5.1 Electrochemical results

The electrochemical characterization output of the capacitor described in Table 3 demonstrates a stable capacitance across a wide range of current values. The specific capacitance per gram of AC decreased slightly from 21 F g⁻¹ at 0.1 A to 19 F g⁻¹ at 10 A, corresponding to a retention of approximately 90%, indicating good performance even at high currents. Similarly, the total cell capacitance decreased from 34 F to 31 F, with a

Table 3 Electrochemical performance of olive pits derived AC-based multilayer pouch cell EDLCs

<i>I</i> (A)	<i>C</i> (F g ^{−1} , AC)	<i>C</i> (F)	<i>E</i> _{drop} (V)	<i>E</i> (Wh kg ^{−1} , AC)	<i>E</i> (Wh)	<i>P</i> (W kg ^{−1} , AC)	<i>P</i> (W)
0.1	21	34	0.012	20.9	0.035	81.4	0.135
0.2	20	33	0.035	19.7	0.033	161.4	0.267
0.3	19	32	0.077	17.4	0.029	223.1	0.369
0.5	19	31	0.120	17.2	0.028	383.6	0.634
1	19	32	0.258	18.9	0.031	801.0	1.324
1.5	19	31	0.266	15.4	0.025	1105.2	1.827
3	19	31	0.309	17.3	0.029	2329.1	3.850
5	19	31	0.380	16.0	0.027	3758.0	6.212
10	19	31	0.474	13.4	0.022	6868.2	11.354

retention of 90%, while the voltage drop (E_{drop}) increased with current, rising from 0.012 V at 0.1 A to 0.474 V at 10 A. The energy density per unit mass of active material decreased from 20.9 Wh kg^{−1} at the lowest current to 13.4 Wh kg^{−1} at the highest current, with total energy following a similar trend. In contrast, the power density exhibited a pronounced increase with current, ranging from 81.4 W kg^{−1} to nearly 6870 W kg^{−1}, reflecting the capacitor's capability to deliver energy rapidly. Overall, these results indicate that the device maintains reasonable capacitance and energy retention while achieving high power performance, confirming its suitability for high-rate charge–discharge applications.

5.2 LCA results

This study aims to determine the potential sustainability implications of using biomass as precursor material in the production of AC and EDLC systems. At the same time, it fills relevant data gaps in the field of LCA for supercapacitors. For which few publicly available information is available. For the LCA analysis, the performance values reported in the first row of Table 3 were used, corresponding to a current of 0.1 A, a capacitance of 34 F, and an energy output of 0.035 Wh. Primary data for the synthesis of AC from olive pits and for the production of a test-cell have been generated and studied to broaden the understanding of the environmental profile. As a by-product of the olive-oil industry. Olive pits are viewed as a low-impact precursor for AC used in EDLC technologies. In this analysis they are treated as an almost burden-free resource. While acknowledging that such assumptions require further analysis. In particular, transportation effects must yet be examined both from an environmental and economic perspective to assess the viability of establishing a region-based AC supply chain.

5.2.1 Activated carbon production. The environmental impacts of AC production (Fig. 2) are illustrated according to the production steps described in section 3.1. All impact categories are reported in Table S23. Primary and secondary pyrolysis together account for approximately 81% of climate-change impacts, 79% of acidification impacts, and 70% of particulate-matter impacts. This result reflects the high electricity demand associated with heating the furnaces to 700 °C and maintaining the target temperature for two hours during each thermal step. The washing process is the main contributor to material-resource use, accounting for approximately 54% of

the total impact, and also represents 18–30% of the other assessed categories. This contribution is primarily associated with hydrochloric acid consumption. Potassium hydroxide used during secondary pyrolysis is another relevant driver, particularly for particulate-matter formation and material-resource use. Argon supply also contributes noticeably to the impacts of both thermal-treatment steps. In contrast, tar treatment contributes only a minor share, while grinding and final drying or storage have negligible contributions.

For a fair comparison with the literature, selected AC-focused studies with disclosed inventories were re-modelled using a harmonized electricity provider (ENTSO-E) and consistent background datasets. Because electricity consumption is a major contributor to the environmental impacts of AC production, this harmonization reduces background variability. The climate-change results are shown in Fig. 3, while the results for all impact categories are reported in Table S24. It should be noted that, in several studies, the calculation of the energy demand associated with the pyrolysis steps is unclear, which affects comparability.

Overall, the olive-pit-derived AC shows higher environmental impacts than most of the literature cases presented in Fig. 3. This is consistent with the low-TRL, laboratory-scale configuration of the current process, which relies on a gram-scale tubular furnace and two separate thermal-treatment steps (primary and secondary pyrolysis). Previous studies have likewise identified electricity consumption as a major contributor to the environmental impacts of laboratory-scale AC production. For instance, electricity accounted for approximately 70% of the total impacts associated with KOH-activated AC derived from cocoa pods.³⁷

Differences in reported impacts may also arise from the treatment of equipment energy. For example, one coconut-shell AC study excluded equipment electricity from the system boundary, resulting in comparatively low impacts,⁴⁵ while other studies reported very low electricity demand for pyrolysis relative to drying, which may reflect larger furnace capacities or optimistic duty-cycle assumption.³⁹

The comparatively high GWP of this system (441.5 kg CO₂-eq per kg AC) is driven by a combination of methodological and scale-related factors. At gram scale, the energy required to heat the furnace is allocated to a relatively small quantity of product, resulting in high electricity consumption per kilogram of AC. The process also involves two heating stages, each

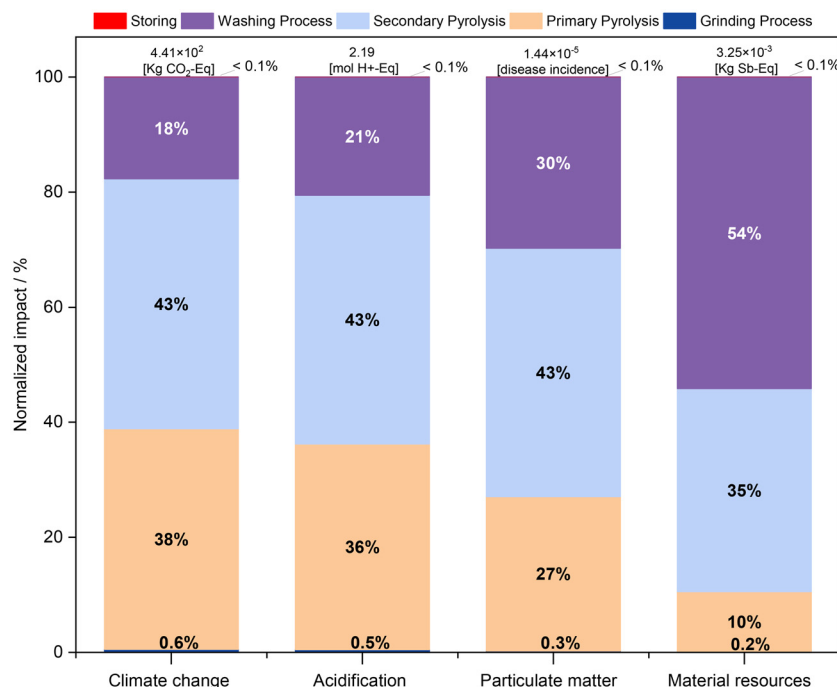


Fig. 2 Environmental profile of the production of 1 kg of AC from olive pits.

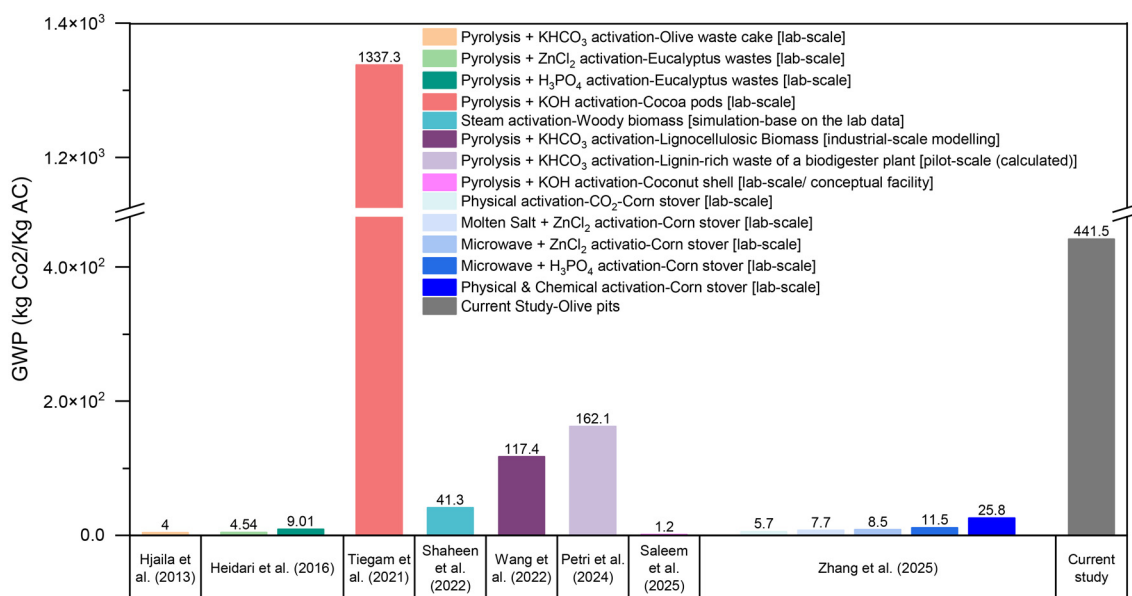


Fig. 3 Comparison of GWP for AC production across different biomass sources and synthesis methods reported in the literature. All cases were evaluated on a harmonized functional unit of 1 kg AC. For studies with original FUs different from 1 kg AC (Tiegam et al. (2021)³⁷: 4 g AC; Wang et al. (2022)¹⁴: 1000 kg AC). The LCIs were scaled to 1 kg AC prior to impact assessment.

with a two-hour holding period, which further increases energy demand. In addition, the estimated electricity consumption per furnace cycle was normalized to the functional unit of 1 kg AC. Given the limited furnace throughput, this conservative approach results in high kWh kg⁻¹ values and is the main reason why the impacts exceed most values reported

in the literature. By contrast, several published LCIs reflect scale efficiencies that are not yet achieved under the current low-TRL production conditions.

The literature indicates three key points. First, scale effects are important, and comparisons between small laboratory systems and industrial processes should therefore be made

cautiously. When production is scaled up and energy or chemical recovery is implemented, the GWP of bio-based activated carbon can decrease to approximately 10–16 kg CO₂-eq per kg AC.^{13,14} Second, chemical activators play a key role. The production and disposal of chemicals such as KOH, KHCO₃, ZnCl₂, and H₃PO₄ often contribute substantially to environmental impacts alongside electricity consumption. Recovering and reusing these activators has been shown to significantly reduce overall burdens.^{13,14,37,39} The choice of synthesis method strongly influences the results. Methods such as CO₂ or steam activation, particularly when powered by renewable electricity, appear to be effective strategies for reducing impacts.²⁷

The present results should be interpreted primarily as indicative of the main environmental hotspots. Recommended actions to lower these impacts include improving thermal efficiency and production scale by transitioning from gram-scale batches to larger-capacity or continuous furnaces equipped with heat-recovery systems; optimizing chemical consumption by reducing the activator dosage and implementing activator recovery; and minimizing washing requirements through measures such as counter-current washing and de-ionized-water reuse. Lastly, given the energy-intensive nature of the overall process, substantial impact reductions could be achieved by decarbonizing the electricity supply.

It should be noted that relying only on a mass-based functional unit (1 kg AC) could hide differences in performance that depend on the intended AC application. Specific uses

(such as adsorption or electrochemical storage) and related properties (pore size distribution, surface chemistry, conductivity, density, *etc.*) could affect the environmental impact per unit of service provided. Reporting an additional service-based functional unit (for example per kg of contaminant removed under defined conditions, or per Wh per cycle at a given voltage, current density, and electrode loading) together with 1 kg AC would allow for a more robust picture of the sustainability profile of AC production.

5.2.2 EDLC production. The production of one EDLC cell is dominated by the positive and negative electrodes, which together account for approximately 82% of the impacts across all four categories. The positive electrode contributes about 42%, while the negative electrode contributes approximately 40% to the total impacts (Fig. 4). In most cases, these contributions are primarily driven by AC production, with an additional share stemming from the direct energy demand associated with electrode fabrication. Manufacturing energy is the next most relevant contribution for ‘climate change’ and ‘acidification’, representing 13% and 12%, respectively, but decreases to 7% for ‘particulate matter’ and 4% for ‘material resources’. The electrolyte contributes only 2–3% in most categories but reaches 12% for ‘material resources’, largely linked to the supply chain of sodium tetrafluoroborate used in the synthesis of tetraethylammonium tetrafluoroborate, which alone contributes around 11%. The pouch accounts for 2–6%, with its highest contribution observed for ‘particulate matter’, mainly due to emissions associated with aluminium pro-

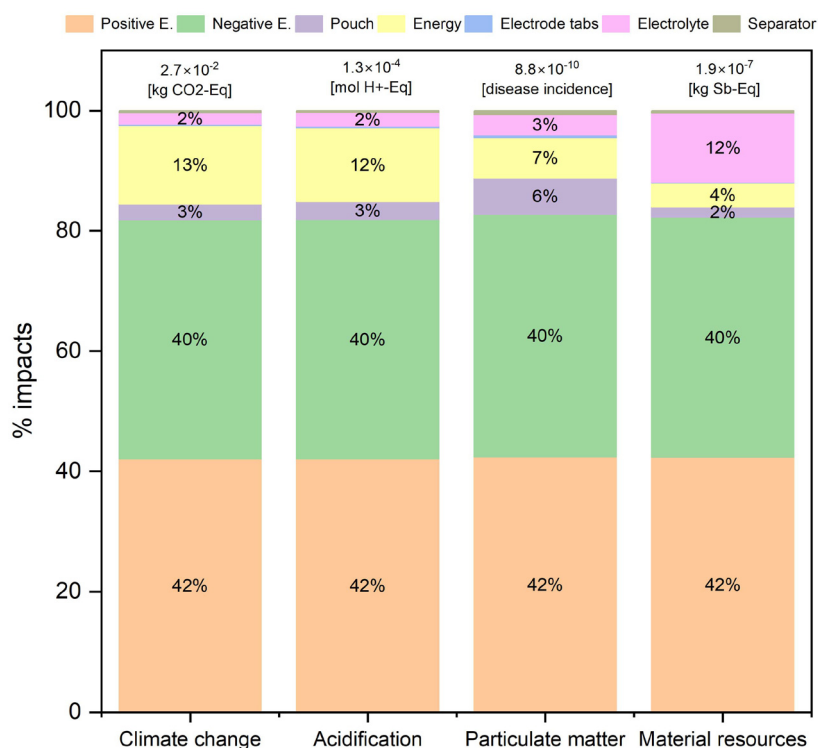


Fig. 4 Environmental profile of the production of an EDLC test-cell with reference AC from olive pits. Impacts per F of capacitance.

duction, whereas the electrode tabs and separator have only marginal contributions. A complete list of results in all impact categories and different functional units is available in the SI (Tables S25 to S27).

It is noteworthy that the environmental profile of the EDLC is heavily influenced by the laboratory-scale production of AC, which involves high specific energy and material demands. The limited throughput of AC production represents a key bottleneck, amplifying specific impacts for both AC and the EDLC cell. The practical upscaling of AC production should prioritize reducing consumption of materials such as hydrochloric acid and potassium hydroxide, which bear significant burdens. Likewise, increasing AC material yield would contribute significantly to lowering the overall impact. To better approximate an industrial context, literature data on higher-scale AC production from olive pits must therefore be integrated, and scenario analyses, such as those presented in section 5.3, are required to reassess the environmental performance of EDLC cell production under more realistic production conditions.

5.3 Scenario analysis

The results so far describe the environmental profile of AC and EDLC cell production at lab-scale level. Although our model considers full equipment utilization, it is likely that the calculated impacts remain largely overestimated with respect to pilot or industrial production. This is particularly critical when looking at the contributions from AC to the total results at the cell level, which largely distorts its profile and hampers its interpretation. To support a more nuanced discussion, the laboratory-scale AC production data were therefore replaced with two different literature-based datasets representing higher production scales, as described in section 4.4. The environmental impacts of the EDLC test-cell production are recalculated considering these two new scenarios, and the results reflect a more heterogeneous distribution of burdens across the different cell components in both cases, as seen in Fig. 5(A) and (B). Notably, there are only small differences in the aggregated impacts between both scenarios (climate change = 5.6×10^{-3} – 5.8×10^{-3} kg CO₂-eq per F; acidification =

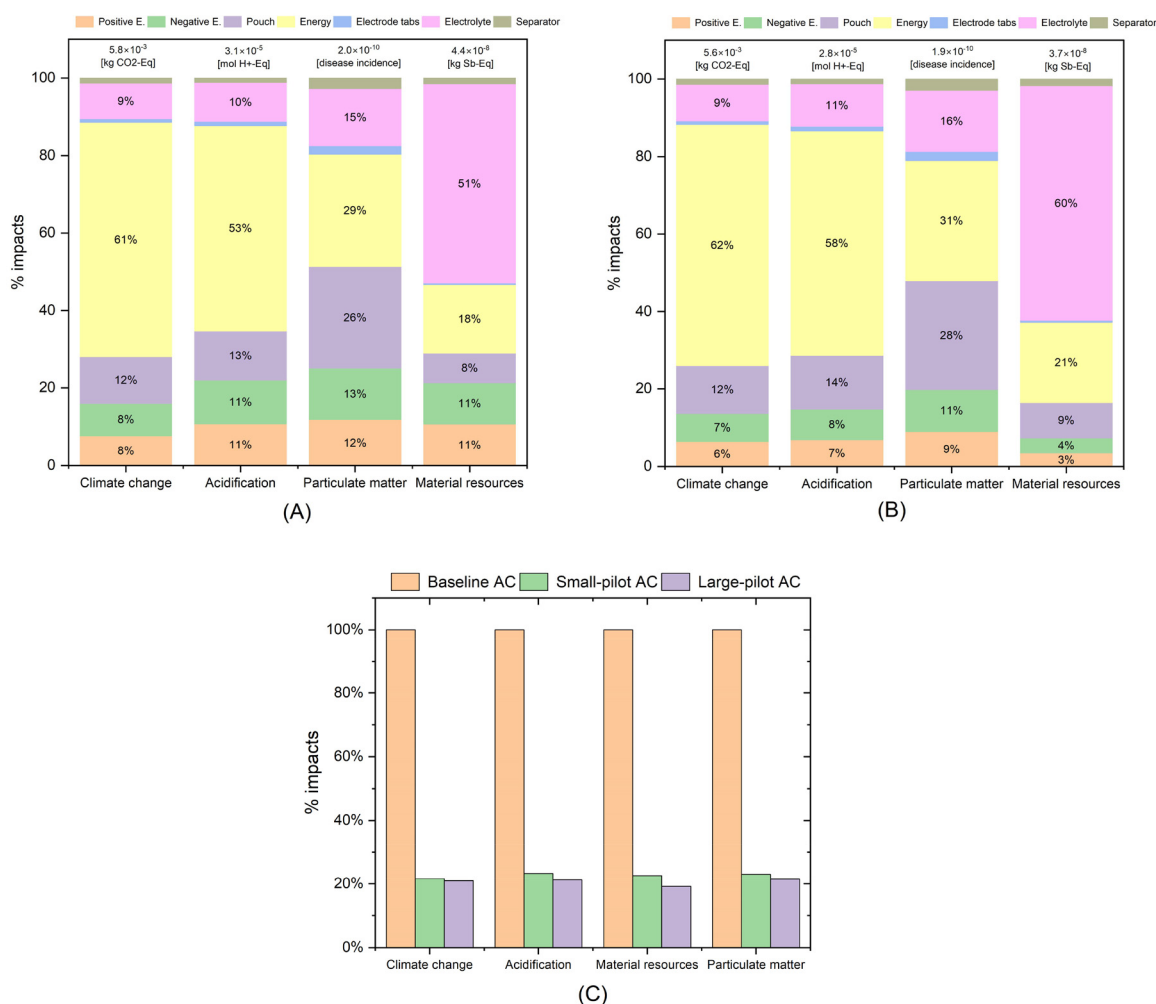


Fig. 5 Environmental performance of EDLC production with different AC production datasets. (A: small pilot AC as described by Hjaila *et al.*; B: large-pilot AC as described by Arena *et al.*; C: comparison between baseline and alternatives). Impacts per F of capacitance.

2.8×10^{-5} – 3.1×10^{-5} mol H^+ -eq per F; particulate matter = 1.9×10^{-10} – 2.0×10^{-10} disease incidence per F; material resources = 3.7×10^{-8} – 4.4×10^{-8} kg Sb-eq per F). This is because the contributions from AC production become less relevant than the impacts from cell manufacturing and other cell components, which are kept the same in both configurations. Energy demand during the cell assembly process stands out as the major contributor in the impact categories ‘climate change’ and ‘acidification’, accounting for about 53–62% of the impacts. The contributions from the electrolyte also gain relevance, representing more than half the total impacts in ‘material resources’. Aside from this, the contributions from both electrodes stem mainly from energy demand used in their production processes (slurry mixing, coating, calendaring, cutting, and drying).

A comparison of the results in the baseline with those of the alternative scenarios indicates that incorporating larger-scale AC production would lead to a significant reduction in the overall impacts of EDLC cell production (Fig. 5(C)). Impacts in all categories drop to roughly 20% of the baseline. These differences are attributed not only to the change in energy demand for AC production across scenarios, but also to the absence of hydrochloric acid and potassium hydroxide in the datasets assumed for AC pilot-scale production. If alternative AC production routes are assumed and integrated into the EDLC model, the overall environmental impact is reduced by more than half compared to the baseline case. As a result, the relative contribution of other processes increases: the dominant hotspots become the direct energy consumption for cell assembly, as well as the impacts associated with electrolyte production. The latter has been modeled based on literature

as no other data is available in commercial datasets, specifically for the synthesis of Tetraethylammonium tetrafluoroborate. Therefore, this model likely reflects a non-optimized version of this process, potentially bearing larger impacts than the industry counterparts. The strong influence of energy demand suggests that the environmental performance of these systems be highly sensitive to the composition of the energy grid, an aspect that should be carefully considered in any large-scale roll-out of supercapacitor production.

Only a few other studies providing a full picture of the potential impacts of supercapacitor production are available. The study by Kamali *et al.*³² has been referenced for comparison, as it is one of the few available analyses calculating the impacts of supercapacitors at the cell level and with a compatible functional unit (FU = 1 F). In their study, the authors calculated the impacts of producing two different cylindrical supercapacitor architectures using either an ionic liquid or sulfuric acid as electrolyte, while sourcing AC for the electrodes from coconut shells. Interestingly, the authors allocated part of the impacts of coconut cultivation to production of AC, in contrast to the burden-free olive pits considered in this study. The authors also calculated mass and energy flows at industrial scale, while considering production taking place in France, thus using its energy mix as supply. Another study modeled a lab-scale coin cell supercapacitor using pyrohydrochar from yard waste as precursor for hard carbon production.⁵³ The same authors considered the Indian energy mix as supply for AC production and cell assembly processes. When looking at results for climate change potential in the literature, the EDLC test-cell bears a carbon footprint sitting in-between that from other reference cells (Fig. 6). The pilot-scale results in this

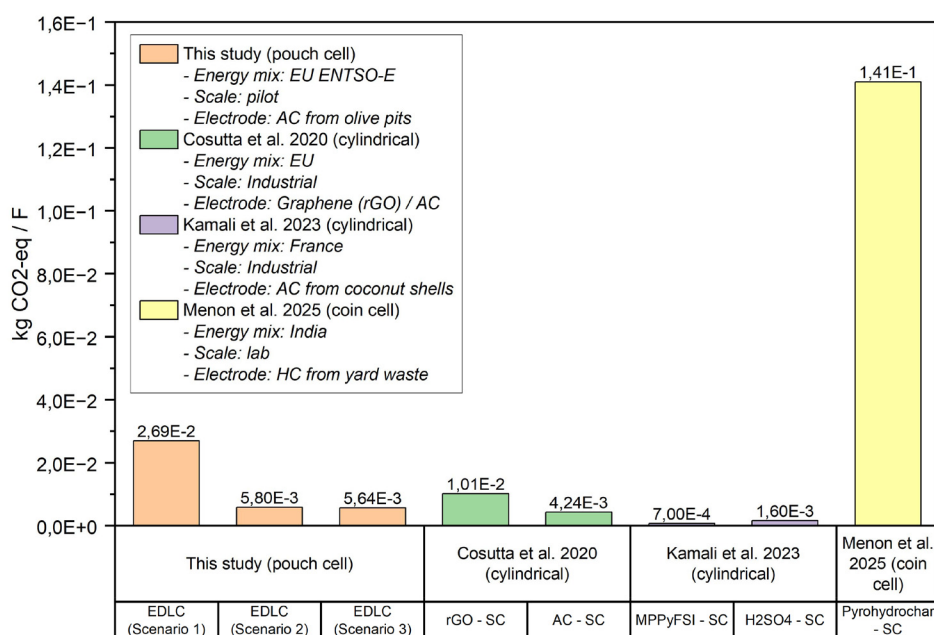


Fig. 6 Carbon footprint comparison of EDLC cell production across this study and selected literature sources. expressed as kg CO₂-eq per F. Scenarios 1–3 represent this work with different AC supply datasets (baseline lab-scale, small-pilot, and large-pilot).

study are about half of the reported values by Cossutta *et al.*³¹ for a cylindrical graphene-based supercapacitor cell, and about 1.4 times higher than their AC-based supercapacitor. They are also between ~3.6 to ~8.3 times higher than the values reported by Kamali *et al.*³² and about ~24 times lower than those from Menon *et al.*⁵³ The pronounced difference with the studies by Kamali *et al.*³² and by Menon *et al.*⁵³ can be partly attributed to the scale of production. Regardless of AC supply, the EDLC pouch test-cell described in this study corresponds to a pilot system, while its counterpart in Kamali *et al.*³² relates to a theoretical model of an industrial-level system in which mass and energy flows benefit from economies of scale. Moreover, the nuclear-intensive French energy mix accounts for roughly one quarter of the carbon footprint per kWh compared to the average European mix used in this study, according to Ecoinvent version 3.12. Likewise, the carbon footprint per kWh of the average Indian mix reported in Menon *et al.*⁵³ is roughly 4.2 times higher than that of the average European mix. The same authors also report significant contributions stemming from the aluminium casing of the coin cell, accounting for more than 50% of the total impacts.

6 Conclusions

Assessing biomass-derived AC for use in EDLCs provides further evidence on the sustainability implications of emerging supercapacitor technologies and helps address persistent data gaps at the device level. According to the available literature, this work is among the first cradle-to-gate LCAs that model a bio-waste-derived AC-based EDLC at the full-cell level, covering AC synthesis, electrode fabrication and multilayer pouch-cell assembly using a combination of primary and secondary manufacturing data. Under the current laboratory-scale AC route, impacts are dominated by thermal processing and reagent-related burdens, indicating that improving process efficiency (*e.g.* reducing energy demand and optimizing reagent use and yield) is critical for lowering impacts. At the cell level, the baseline EDLC profile is strongly influenced by the laboratory-scale AC inventory; when higher-scale AC datasets are substituted, total impacts decrease substantially and the dominant hotspots shift toward assembly energy demand and electrolyte supply. Overall, olive-pit-derived AC represents a technically viable electrode precursor for EDLCs, with environmental performance that is highly dependent on production scale and process integration. The findings go in line with referenced literature on supercapacitor production at different scales. The potential impacts of the pilot-scale system in this study are comparable those from supercapacitors produced at industrial-scale, as seen when contrasting with the studies from Cossutta *et al.*³¹ and Kamali *et al.*³² and smaller than those from Menon *et al.*⁵³ reported for a lab-scale production line. This highlights the large potential for impact reduction of supercapacitors due to the effects of economies of scale, which has also been observed in the lithium-ion battery industry.⁵⁴ Notably, the scenario analysis suggests that, if pro-

duction is optimized, the active material could bear minor contributions to the overall picture. In combination with promising technical performance, biomass could become a sustainable source of precursor material in the production of EDLCs. Future work should evaluate higher-throughput AC production routes, improve the modelling of electrolyte synthesis, investigate water-processable alternatives to the PVDF/NMP-based electrode formulation, and extend the assessment to the use and end-of-life stages as more representative data become available.

Author contributions

F. B.: writing—original draft, writing – review and editing, visualization, methodology, investigation, formal analysis, data curation, and conceptualization. S. P. B.: writing – original draft, writing – review and editing, visualization, methodology, formal analysis, data curation, and conceptualization. M. A.: writing – original draft, writing—review and editing, methodology, investigation, formal analysis, data curation, and validation. J. A.: writing – review and editing, validation, supervision, resources, investigation, data curation, and project administration. M. W.: writing – review and editing, validation, supervision, resources, conceptualization and project administration.

Conflicts of 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.

Data availability

The raw data supporting the conclusions of this article will be made available by the authors upon request.

Supplementary information (SI) is available. The Supplementary Information contains detailed life cycle inventory data and calculation procedures for activated carbon and EDLC production, EDLC energy-demand calculations, and complete life cycle impact assessment results for AC and EDLC production. See DOI: <https://doi.org/10.1039/d6gc03362h>.

Acknowledgements

Authors would like to acknowledge The MUSIC project Funded by the European Union's Horizon Europe Research and Innovation program under grant agreement number 101092080. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. This work contributes to the research performed at CELEST (Center for

Electrochemical Energy Storage Ulm-Karlsruhe). The authors Marcel Weil, Sebastian Bautista and Fatemeh Bahmei acknowledge the financial support by the German Research Foundation (DFG) under Project ID 390874152 (POLiS Cluster of Excellence. EXC 2154).

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