

AGRITECH

National Research Centre for Agricultural Technologies

BOtanical REsources for ALternative battEries - “BO.RE.AL.E.”

**AMBITO: NUOVE MOLECULE, PRODOTTI E PROCESSI AD
ALTRO VALORE AGGIUNTO PER LA VALORIZZAZIONE DI
RIFIUTI, SCARTI, SOTTOPRODOTTI E COPRODOTTI AGRICOLI
O PER L'AGRICOLTURA**

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Deliverable: D4.2

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2. EXECUTIVE SUMMARY

This study presents a Life Cycle Assessment (LCA) of innovative "green" electrodes incorporating Carbon Dots (CDs) synthesized from agricultural by-products, aiming to promote more sustainable and circular approaches in energy storage materials. The analysis follows the ISO 14040/14044 standards and adopts a cradle-to-gate system boundary. The functional unit is defined as 1 Ah of stored electric charge, allowing for meaningful comparisons between different electrode technologies. The Environmental Footprint 3.1 (EF 3.1) method was selected to quantify environmental impacts, as it offers comprehensive, harmonized indicators suitable for European and policy-aligned studies.

Results show that the CDS-based cathode achieves a 40% reduction in total environmental impact, despite requiring a larger mass to store the same charge. The most significant improvements are observed in the "Resource use, minerals and metals" category, due to the absence of metal-based active materials. These findings confirm the environmental potential of bio-based electrodes and suggest that further benefits can be achieved through process optimization and renewable energy integration.

3. INTRODUCTION

LCA is a well-established tool used to evaluate the environmental impacts of products and processes throughout their life cycle, following the standards UNI EN ISO 14040 and 14044. According to these standards, every LCA study must begin with a clear definition of its **goal and scope**: the goal of this study is to assess the environmental impact of "green" electrodes containing CDs synthesized from agricultural by-products, promoting a circular and sustainable approach in the production of energy storage materials. This study is intended for researchers, professionals, and stakeholders involved in the development of more sustainable energy technologies.

The results of the study aim to:

- compare these electrodes with conventional alternatives
- identify the most environmentally impactful stages of the process
- provide insights for possible improvements and environmental optimizations.

The selected **functional unit** is the storage of 1 ampere-hour (1 Ah) of electric charge. This choice allows for a fair and meaningful comparison of the functional performance of the studied electrode with alternative technologies available on the market, in terms of energy storage capacity.

As show in **Figure 1**, the product system analysed in this study consists of several interconnected unit processes, where the output of each process serves as the input for the next. Specifically, three main

processes are considered: the synthesis of CDs from agricultural by-products, the formulation of the slurry containing the CDs, and the fabrication of the electrode using the resulting slurry.

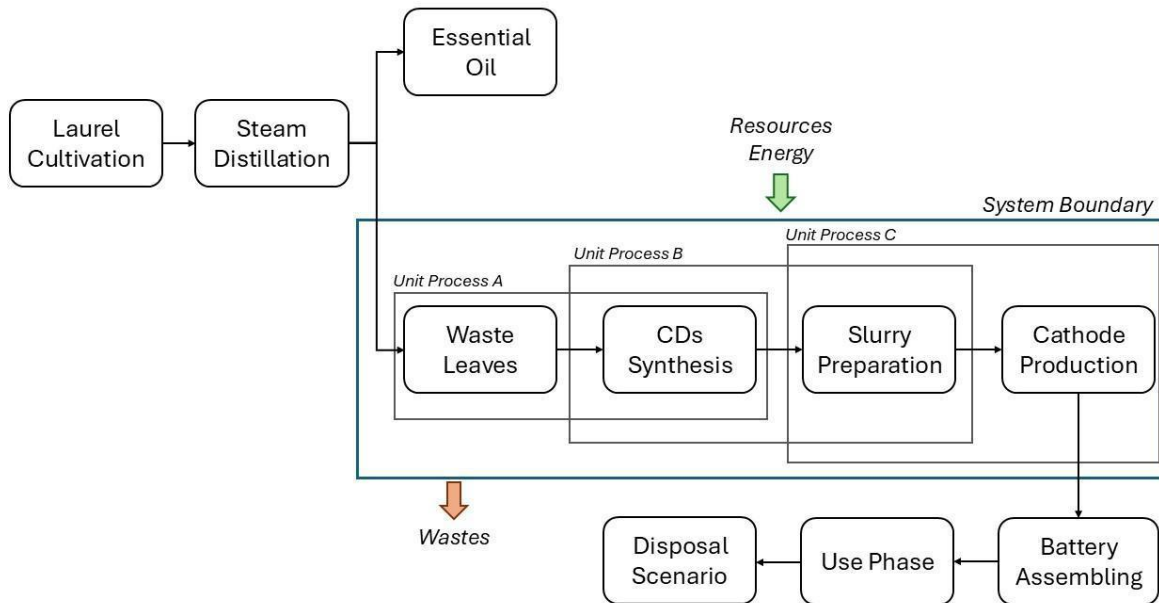


Figure 1: Flow diagram of the system under study.

Regarding the **system boundaries**, which define which process stages, material flows, and energy flows are included in the analysis, a cradle-to-gate approach was adopted. This includes all life cycle stages from the acquisition of raw materials up to the point where the electrodes leave the laboratory in which they were manufactured.

The latter stages (battery pack assembly, integration into electronic devices, and the use phase) are not considered, as they are assumed to be identical for both the studied electrode and conventional alternatives. Transport phases are also excluded, assuming the raw material comes from local sources, and to keep the focus on the production process.

ISO 14044 asks to specify whether allocation procedures were used. Since the plant resource identified as the best from an electrochemical and environmental point of view is laurel leaves from the essential oil extraction process, it was not necessary to implement allocation procedures since these enter the system under study with zero environmental load.

The study is based on data representative of the Italian context in 2025.

4. METHODOLOGY

The analysis was conducted using the SimaPro 10.2 software.

The Environmental Footprint 3.1 (EF 3.1) method, developed by the Joint Research Centre (JRC) of the European Commission, was adopted for the Life Cycle Impact Assessment (LCIA) phase. The choice of this method is motivated by the desire to ensure consistency with European guidelines for quantifying the Product Environmental Footprint (PEF). In addition, EF 3.1 is compatible with LCI databases developed specifically for PEF-compliant applications, ensuring consistency between inventory and impact model.

The EF 3.1 method allows inventory flows to be transformed into potential environmental impacts through characterization factors based on scientific models updated to the European context. The following 16 environmental impact categories are considered: “Climate change”, “Ozone depletion”, “Human toxicity -cancer effects”, “Human toxicity, non-cancer effects”, “Particulate matter, diseased cases”, “Ionising radiation”, “Photochemical ozone formation”, “Acidification”, “Eutrophication, terrestrial”, “Eutrophication, freshwater”, “Eutrophication, marine”, “Ecotoxicity, freshwater”, “Land use”, “Water use”, “Resource use, energy carriers”, “Resource use, mineral and metals”.

4.1 Life Cycle Inventory (LCI)

The input and output data used in this inventory were obtained from previous laboratory experiments. These quantities, such as the masses of raw materials and reagents, were measured directly during experimental procedures and are therefore considered primary data.

However, while the quantities were determined through direct observation, the background information (such as production processes, upstream supply chains, and transportation) associated with each material was not modelled manually. Instead, environmental profiles were selected from the databases available in the SimaPro software. As such, the life cycle data used to represent the environmental burdens of materials and energy flows are classified as secondary data, in line with standard LCA practice.

Regarding electricity consumption, a different approach was required. Since real-time measurements were not available for all instruments, energy use was estimated based on the technical specifications (nominal power and operation time) of each device. Because the instruments operated at varying power levels that were not directly measurable, assumptions were made to estimate their actual energy use. The data were validated through a combination of consistency checks and technical plausibility assessments.

A critical issue in laboratory-scale LCA is the accurate estimation of energy consumption, which tends to be overestimated when the full energy demand of a laboratory instrument is attributed to a small quantity of processed material. To avoid this distortion, we adopted a weighted allocation approach based on the instrument's maximum or realistic operational capacity.

This means that the estimated energy use was allocated across the theoretical full load the equipment could process in a single cycle, rather than solely on the small experimental batch size. This methodological choice ensures a more realistic and representative energy impact per functional unit and supports more reliable comparisons across different process steps or design alternatives.

➤ Microwave Oven

The energy consumption associated with the use of a Midea microwave oven (nominal power: 700 W) was calculated. The microwave was operated for 3 minutes, assuming it was loaded with 6 test tubes, each with a maximum capacity of 80 mL. This setup matches the full capacity of the centrifuge used in the following step. The decision to use the same quantity in both the microwave and the centrifuge was made to ensure greater data consistency and to better simulate the actual process. Each test tube contained 6 g of leaves and 40 ml of water, for approximately 46 g of solution per tube, equivalent to twice the amount actually tested (3 g of leaves and 20 ml of water).

The total mass processed per cycle was therefore 276 g.

Total energy consumption:

$$0,7 \text{ kW} \times 0,05 \text{ h} = 0,035 \text{ kWh} \quad \text{eq. (1)}$$

Specific consumption:

$$0,035 \text{ kWh} / 276 \text{ g} = 0,000127 \text{ kWh/g} \quad \text{eq. (2)}$$

Referred to 23 g:

$$0,000127 \times 23 = 0,0029 \text{ kWh} \quad \text{eq. (3)}$$

➤ Centrifuge

To estimate the energy consumed by the centrifuge operating at 10.000 rpm, the cube law was applied. This principle states that power demand in centrifugal systems varies with the cube of the speed ($P \propto \text{rpm}^3$). Assuming a nominal power of 2,5 kW at 30.000 rpm, the rotational power at 10.000 rpm is:

$$2,5 \text{ kW} \times (10.000 / 30.000)^3 = 92,6 \text{ W} \quad \text{eq. (4)}$$

Additionally, a baseline power demand (independent of rotational speed), due to electronics, control systems, and cooling, was assumed as 10% of the nominal power. Thus, the total estimated power is:

$$92,6 \text{ W} + 250 \text{ W} = 342,6 \text{ W} \quad \text{eq. (5)}$$

Energy consumption over 30 minutes (0,5 h):

$$342,6 \text{ W} \times 0,5 \text{ h} = 0,171 \text{ kWh} \quad \text{eq. (6)}$$

Specific consumption:

$$0,171 \text{ kWh} / 276 \text{ g} = 0,000621 \text{ kWh/g} \quad \text{eq. (7)}$$

Referred to 23 g:

$$0,000621 \times 23 \text{ g} = 0,0142 \text{ kWh} \quad \text{eq. (8)}$$

➤ Drying Oven

The drying oven has a nominal power of 1,2 kW and was operated at 40°C for 24 hours. Since the oven was not used at full power, it was assumed that the power consumption is proportional to the set temperature, based on a maximum operating temperature of 230°C.

Under these assumptions, the estimated power at 40°C is:

$$(40 / 230) \times 1,2 \text{ kW} = 0,21 \text{ kW} \quad \text{eq. (9)}$$

Total energy consumption:

$$0,21 \text{ kW} \times 24 \text{ h} = 5,04 \text{ kWh per cycle} \quad \text{eq. (10)}$$

The oven has a volume capacity of 56 liters and was loaded with 108 test tubes per cycle (3 trays with 36 tubes each). Each tube contained approximately 6 g of leaves and 40 ml of water, for a total of 46 g of solution per tube.

Total processed mass per cycle:

$$108 \text{ tubes} \times 46 \text{ g} = 4.968 \text{ g} \quad \text{eq. (11)}$$

Specific energy consumption:

$$5,04 \text{ kWh} / 4.968 \text{ g} = 0,00101 \text{ kWh/g} \quad \text{eq. (12)}$$

Referred to the functional unit (23 g):

$$0,00101 \times 23 \text{ g} = 0,0232 \text{ kWh} \quad \text{eq. (13)}$$

Below are data sheets for each unit process and a flow diagram representing the interaction between the different processes.

Made by: University of Salento				Completion date: 07/25	
Unit process identification: Unite Process A - Laurel CDs synthesis				Time Period: 2024/2025	
Description of the unitary process: synthesis of CDs from Laurel Leaves					
	Unit	Amount	Type of data	Source of data	Comment
Material Elements Input					
Laurel leaves	g	3	Measured	I	
Milli-Q water	mL	20	Measured	II	
Water Consumption					
Tap Water	L	0,5	Measured	II	
Input Energy					
Electricity	kWh	0,142	Calculated	II	Allegra 64R centrifuge 10000 rpm x 30 min
Electricity	kWh	0,00292	Calculated	II	Microwave Midea MM720CTB 700 W x 3 min
Electricity	kWh	0,0232	Calculated	II	Oven 40°C x 24 h
Material Elements Output					

Waste Water	L	0,52	Calculated	II	Wash water + supernatant
Laurel Cds	mg	200	Measured		

Table 1: data sheet for unit process A – Laurel Cds synthesis.

Made by: University of Salento				Completion date: 07/25	
Unit process identification: Unite Process B - Slurry preparation				Time Period: 2024/2025	
Description of the unitary process: preparation of slurry containing CDS					
	Unit	Amount	Type of data	Source of data	Comment
Material Elements Input					
Laurel Cds	mg	11,7	Measured	I	
N-methyl-2-pyrrolidone	mg	309	Measured	II	
Polyvinylfluoride*	mg	5,7	Measured	II	
9,10-Anthraquinone	mg	27,7	Measured	II	
Carbon Black	mg	11,3	Measured	II	
Water Consumption					
Input Energy					
Electricity	kWh	0,0000094	Calculated	II	UltraTurrax Stirring
Material Elements Output					
N-methyl-2-pyrrolidone	mg	309	Calculated	II	Under the hood, in the air
Slurry	mg	56,4	Measured		

Table 2: data sheet for unit process B – preparation of slurry containing CDS.

*Since PVDF is not available in the Ecoinvent database, polyvinyl fluoride was used instead, as it has comparable environmental impacts, though slightly lower.

Made by: University of Salento				Completion date: 07/25	
Unit process identification: Unite Process C – Cathode Production				Time Period: 2024/2025	
Description of the unitary process: electrode construction					
	Unit	Amount	Type of data	Source of data	Comment
Material Elements Input					
Slurry	mg	1,9	Measured	I	
Aluminium collector foil	mg	12	Measured	II	1 × 4 cm, thickness 15 μm
Water Consumption					
Input Energy					

Electricity	kWh	0,000233	Calculated	II	Heat Plate
Material Elements Output					
Cathode	mg	13,9	Calculated	II	

Table 3: data sheet for unit process C – cathode production.

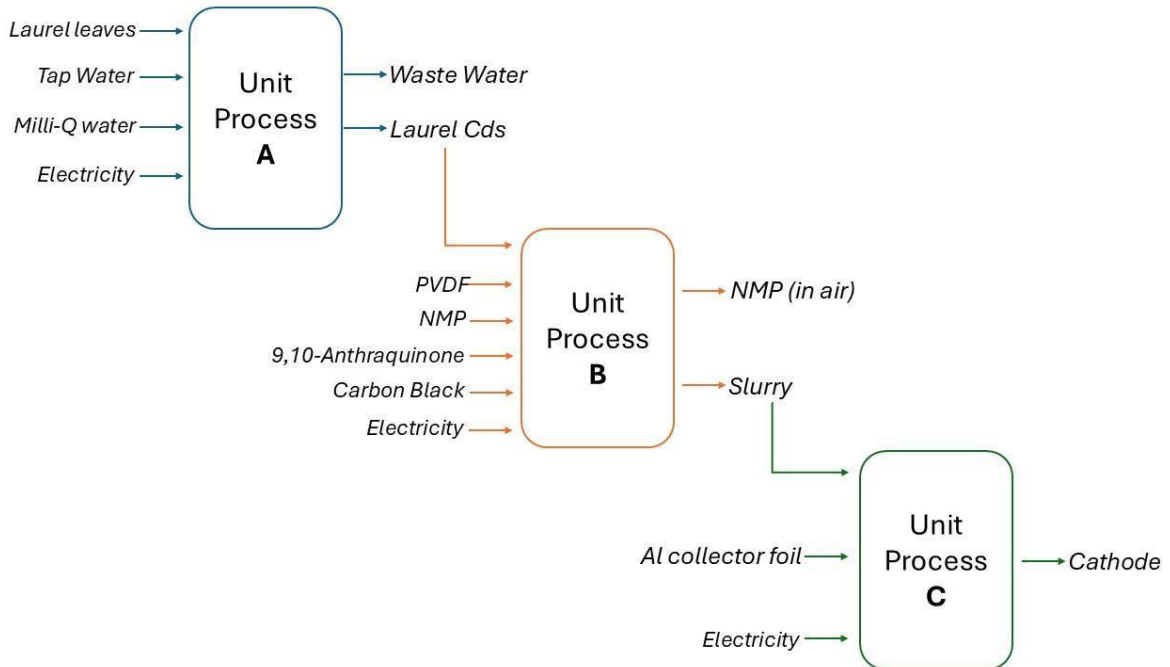


Figure 2: flow chart of the unit processes.

5. RESULTS AND DISCUSSION

The network diagram shown in **Figure 3** clearly illustrates the intersection between the various unit processes, reporting the quantities required to produce one electrode (13.9 mg by weight).

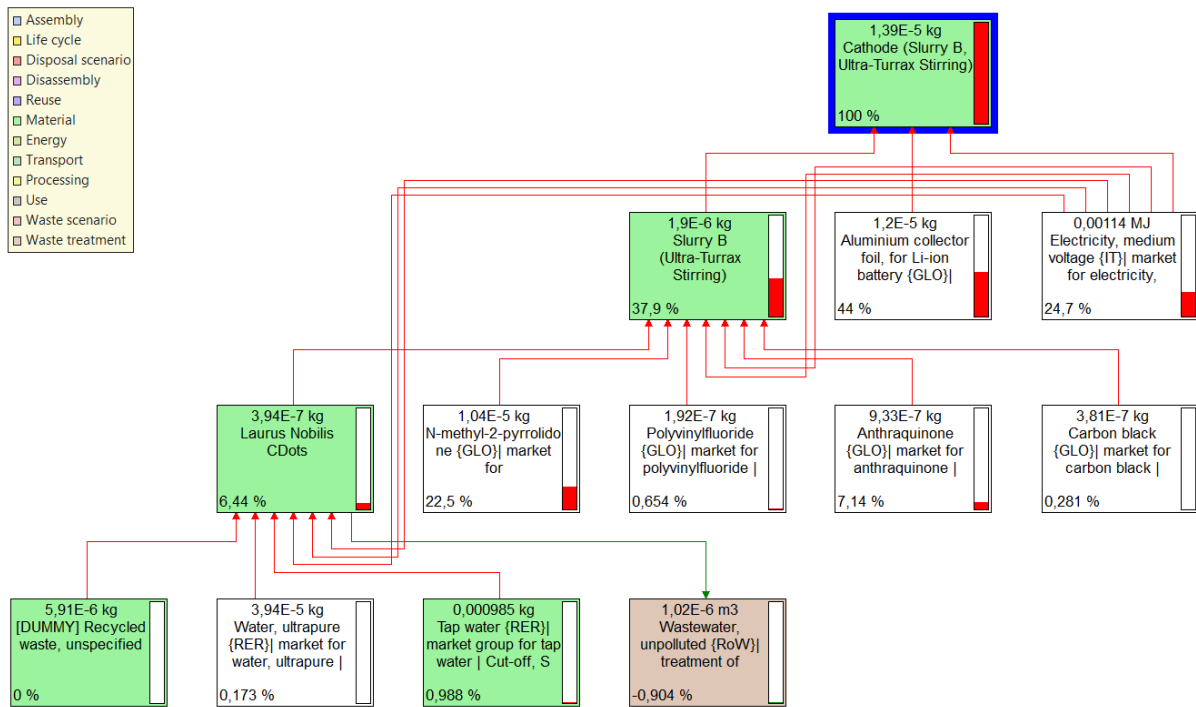


Figure 3: network of production process.

From the diagram, it is evident that the 44% of the total environmental impact is associated with the aluminium foil used as the current collector. The slurry accounts for approximately 38% of the impacts, mainly due to the presence of PVDF and anthraquinone, followed by the electricity consumed during the preceding synthesis phase of the carbon dots.

Overall, electricity consumption contributes about 25% of the total impact, highlighting a clear opportunity for future process optimization.

Life Cycle Impact Assessment (LCIA)

The environmental impacts associated with three key components of the electrode production process (slurry preparation (Slurry B with Ultra-Turrax stirring), aluminium collector foil, and electricity consumption (medium voltage, IT mix)) were assessed using the Environmental Footprint (EF) 3.1 method. The results, expressed in millipoints (mPt), are presented in **Figure 4** and allow for a comparison of their relative contribution across all impact categories.

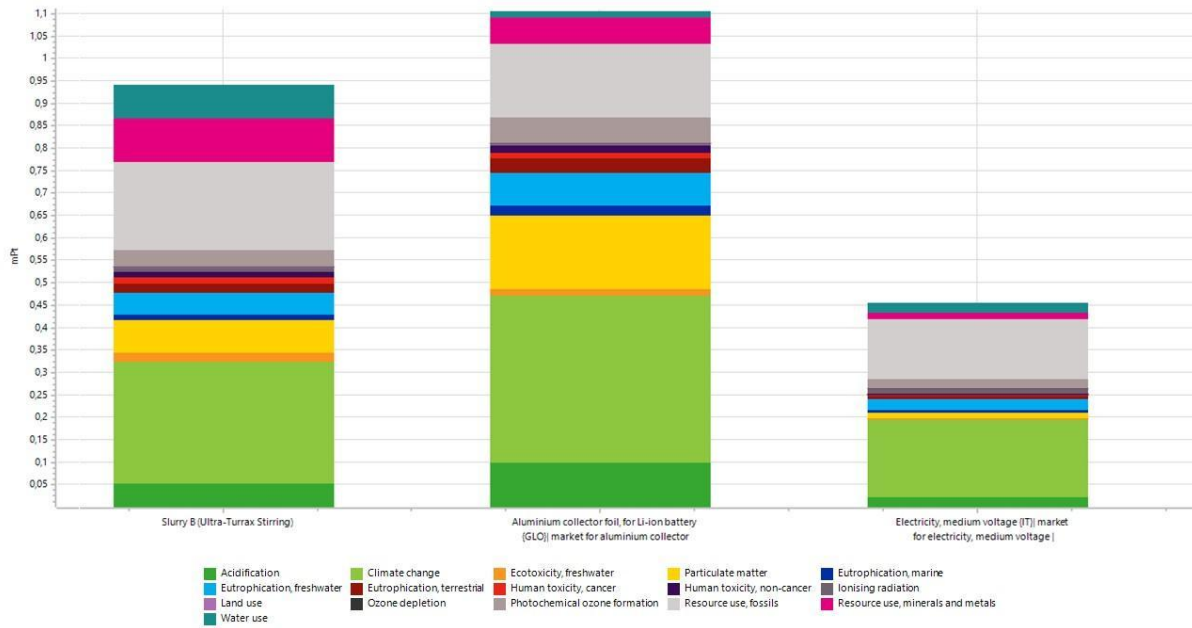


Figure 4: environmental impact of cathode's components.

The environmental burden associated with the slurry preparation phase reaching nearly 1 mPt. Major contributing impact categories include “Climate change”, “Resource use, fossil” and “Resource use, minerals and metals”. These impacts arise primarily from the use of chemical reagents and solvents, as well as from the energy required for CDs synthesis.

The aluminium collector foil shows the highest overall environmental impact, slightly exceeding 1 mPt. This is largely due to the energy-intensive nature of aluminium production, especially when primary aluminium is used. Key impact categories include “Climate change”, “Particulate matter”, and “Fossil Resource use”.

Given the magnitude of its environmental contribution, the aluminium foil stands out as the dominant hotspot within the assessed processes. Substituting primary aluminium with recycled aluminium, or optimizing the thickness and usage of the foil, could offer significant improvements.

Although electricity consumption has the lowest overall impact among the three assessed elements (less than 0.5 mPt), its contribution is still relevant, particularly in categories such as “Climate change” and “Resource use, fossil”.

For comparison purposes, a widely used commercial cathode material was selected: NMC 811 (LiNi_{0.8}Mn_{0.1}Co_{0.1}O₂). The comparison was based on the previously defined functional unit, corresponding to the storage of 1 Ah of electric charge.

Using the specific capacities of the two materials, the amount of active material needed to deliver 1 Ah was calculated:

- NMC 811 (specific capacity ≈ 200 mAh/g): $\frac{100 \text{ mAh/g}}{200 \text{ mAh/g}} = 5 \text{ g}$ eq. (14)

- Developed C-dot cathode (specific capacity $\approx 150 \text{ mAh/g}$): $\frac{100 \text{ mAh/g}}{150 \text{ mAh/g}} = 6.67 \text{ g}$ eq. (15)

Despite the need for a larger amount of cathode material produced using CDs from bay leaves to store the same amount of electric charge as a commercial cathode, the comparative analysis clearly shows that the novel cathode exhibits significantly lower environmental impacts, approximately 40% less in terms of total impact, as shows in **Figure 5**.

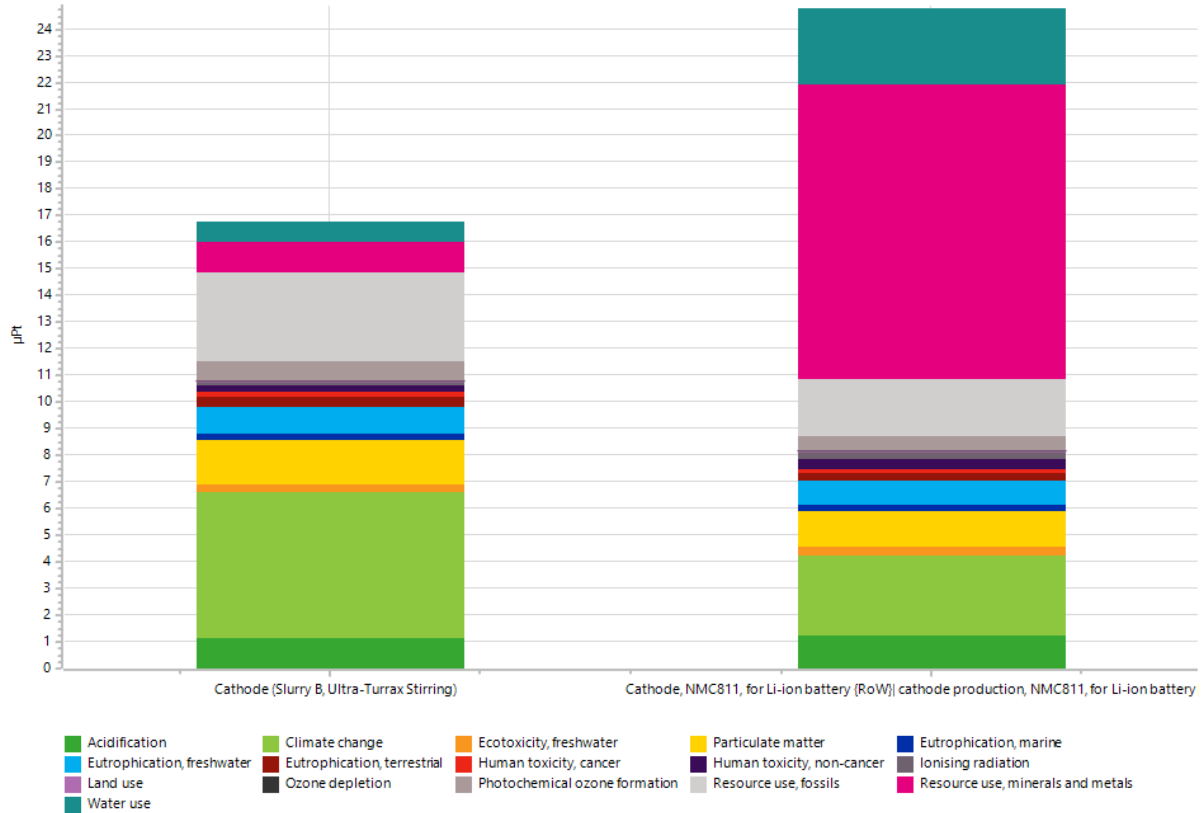


Figure 5: comparison of the environmental impact of the new cathode with NMC811 cathode.

The most pronounced improvement is observed in the impact category "Resource use, minerals and metals", likely due to the absence of metal-based active materials in the CDS-based cathode. Unlike many commercial cathodes that contain transition metal oxides such as manganese, cobalt, nickel, or iron, the cathode developed in this study relies solely on carbon structures derived from agricultural biomass. This significantly reduces the demand for metal extraction and processing, contributing to a lower impact in this category.

A substantial reduction in "Water use" is also evident. In the production process, water is only used to wash the laurel leaves and subsequently as a solvent, in minimal quantities.

Conversely, the analysed cathode shows a higher impact in the "Resource use, fossils" category, approximately twice that of the conventional counterpart. This outcome can be attributed to the use of fossil-derived materials such as N-methyl-2-pyrrolidone (NMP), anthraquinone, and polyvinylidene fluoride (PVDF) in the slurry preparation, as well as the use of energy demand associated with the

production of the CDSs. The model was developed using the Italian electricity mix, without assuming the potential use of renewable electricity. Moreover, as already noted, the process is currently carried out at laboratory scale and is therefore not yet optimized in terms of energy efficiency, a condition expected to improve with future upscaling.

6. CONCLUSIONS

The Life Cycle Assessment performed in this study provides a comprehensive evaluation of the environmental profile associated with the production of an innovative cathode based on CDs obtained from laurel leaves biomass, in comparison with a conventional commercial cathode.

Among the individual process steps, the use of aluminium foil as current collector emerged as the most significant environmental hotspot. Strategies such as reducing foil thickness or replacing primary aluminium with recycled aluminium could substantially mitigate this burden.

The slurry preparation phase, despite being a wet-lab process, also showed a considerable contribution to the overall impact, driven by the consumption of chemical reagents and solvents, as well as the energy demand associated with CDS synthesis. These findings underscore the importance of optimizing material use and energy inputs even at early production stages.

Electricity consumption, although the least impactful among the three elements assessed, indicates that improving energy efficiency or adopting low-carbon energy sources could bring meaningful reductions in overall impact.

The comparative analysis between the bio-based and the commercial cathode highlights the environmental advantages of the former. Despite requiring a greater mass to achieve the same charge storage, the Laurel CDs-based cathode demonstrates a 40% reduction in total environmental impact. The most notable improvement is observed in “*Resource use, minerals and metals*”, likely due to the substitution of metal-based active materials with bio-derived carbon from agricultural waste.

In conclusion, this study demonstrates the environmental potential of biomass-derived electrodes. Even at laboratory scale, the CDS-based cathode outperforms its commercial counterpart in most impact categories. These results suggest that further improvements, particularly through energy source transition and process scale-up, could lead to high-performance, low-impact electrode materials, contributing to more sustainable energy storage technologies.