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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2. EXECUTIVE SUMMARY

This report presents the environmental impact assessment of an innovative green electrode developed from agricultural waste, within a Life Cycle Assessment (LCA) framework adopting the Environmental Footprint 3.1 (EF 3.1) methodology. The analysis focuses on the production phase of the electrode, evaluating the relative contribution of each input material and energy flow. The results indicate that aluminum foil is the primary hotspot, followed by the slurry (mainly due to the use of NMP), and electricity. Impact results were further disaggregated by impact categories and compared with a conventional NMC811 cathode, normalized by capacity (1 mAh). The results show a significant reduction in the "Resource use, minerals and metals" category due to the absence of critical metals in the green electrode. Although impacts in other categories remain comparable, optimization strategies are identified to further enhance environmental performance. The study confirms the potential of bio-based electrodes as a promising solution for sustainable energy storage systems.

3. INTRODUCTION

The increasing demand for energy storage technologies is raising concerns about their environmental footprint, especially due to the use of critical raw materials like nickel, manganese, and cobalt in traditional cathodes (e.g., NMC811). To reduce these impacts, this study investigates a new bio-based cathode made from agricultural residues.

A Life Cycle Assessment (LCA) was conducted using the EF 3.1 method, focusing on the production stage of the electrode. The aim is to identify which materials or energy sources contribute most to the environmental impact and to compare the results with a conventional NMC811 cathode.

The analysis examines impact contributions across different environmental categories. The unit of comparison is based on 1 mAh of charge storage capacity, making the results relevant to practical battery applications.

This work helps identify environmental hotspots, supports eco-design choices, and contributes to developing sustainable battery materials.

4. METHODOLOGY

The results presented in this report are part of a Life Cycle Assessment (LCA) study carried out using a cradle-to-gate approach. This means that the analysis includes all stages from raw material extraction to the production of the final electrode. The functional unit chosen for the study is the accumulation of 1 mAh of electrical charge, which allows comparison based on battery performance. However, the impact values shown in the main results refer to the 13.9 mg of cathode material actually produced during the experimental process.

For the comparison with a conventional NMC811-based cathode, the analysis was scaled based on specific capacity values. In this case, 5 g of NMC811 was compared to 6.67 g of the new bio-based electrode, to ensure both materials deliver the same storage capacity. This approach allows a fair environmental comparison between the traditional and the sustainable cathode technologies.

5. RESULTS AND DISCUSSION

Figure 1 shows a tree diagram that helps visualize the different inputs involved in the production process of the green electrodes made from agricultural waste. Each box in the diagram represents a process input and is color-coded according to its type (materials, energy, waste). The thickness of the arrows shows how much each input contributes to the overall environmental impact. Next to each box, a red bar shows the environmental score in Pt (unit used for expressing the environmental impact), indicating how much each input weighs in the total impact**.**

From the diagram and the associated data, we can see that the aluminium foil has the highest environmental impact, followed by the slurry, which is strongly influenced by the use of the solvent NMP. Other contributors, with lower impacts, are anthraquinone and organic CDs, which are produced from bay leaves left over after essential oil extraction. The impact of CDs mainly depends on the energy used in the synthesis process, but it is still much lower compared to aluminium foil and NMP.

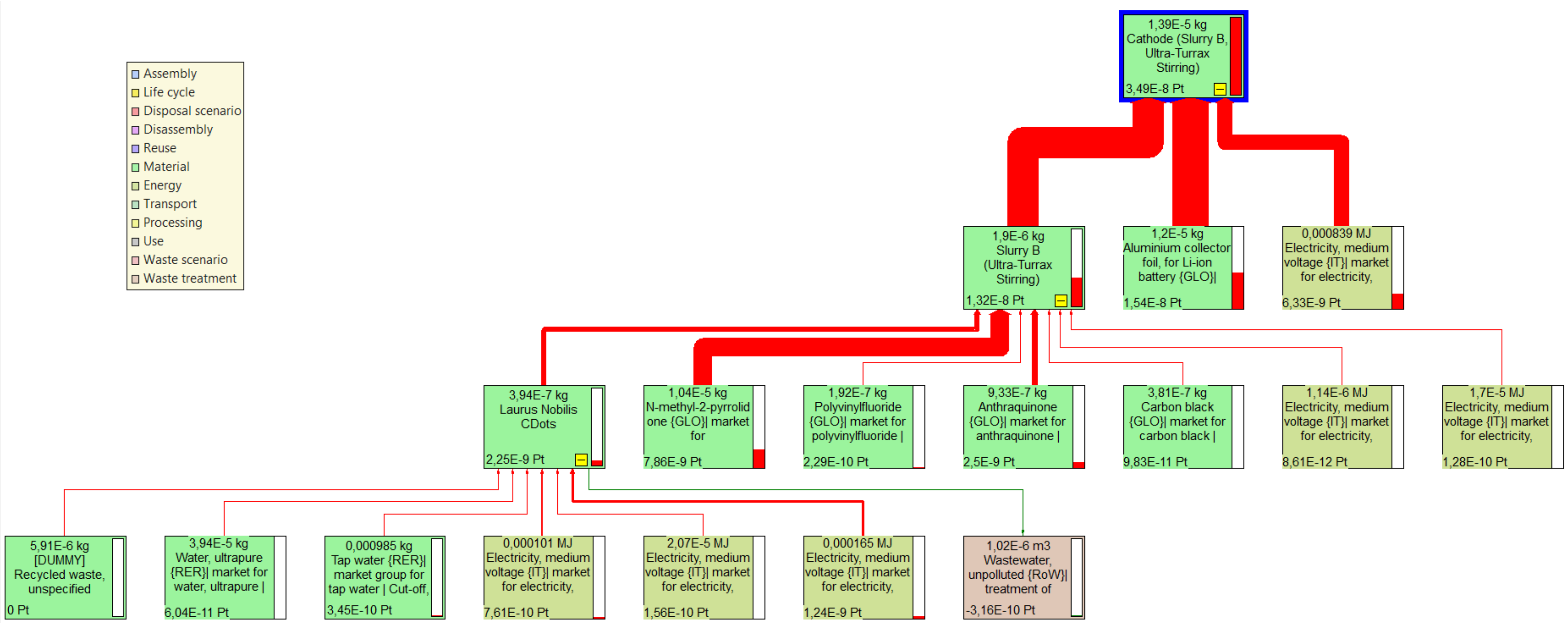

***Figure 1**: network diagram of the manufacturing process of a 13.9 mg electrode.*

In **Figure 2**, looking at the impact of each cathode component across environmental categories (using normalized values), the largest contribution is found in the category "*Resource Use, Fossils*", followed by "*Eutrophication, freshwater*" and "*Climate change*". In the first two categories, aluminium foil and slurry have similar impacts, while electricity, which comes from multiple units processes, has a slightly lower but still important contribution. For “*Climate change*”, aluminium has the highest impact, followed by slurry, with electricity contributing about half as much as those two.

The other impact categories show much lower values, and some of them , like "*Land Use*" and "*Ozone Depletion*", are almost negligible.

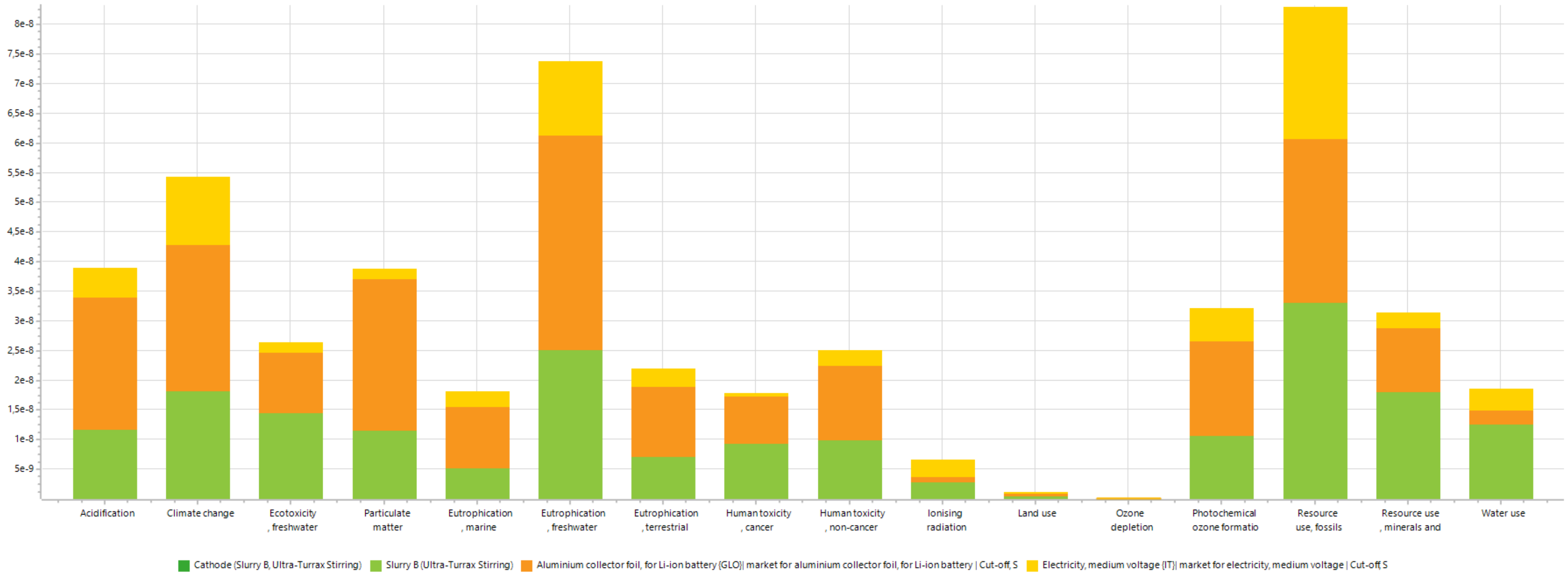

Figure 2*: normalized value for each impact category, for the 3 different electrode components.*

To get a more detailed view of the overall environmental impact (expressed in nPt), in **Figure 3** the slurry was broken down into its individual components. In this more detailed analysis, aluminum foil remains the most impactful input, but electricity (now shown as the total consumption across all unit operations) becomes the second most impactful. NMP comes third, with a slightly lower impact than electricity, followed by anthraquinone, whose impact is about four times smaller. All other inputs contribute very little. It is important to note that the slurry's impact appears low because its contribution is split across several sub-inputs.

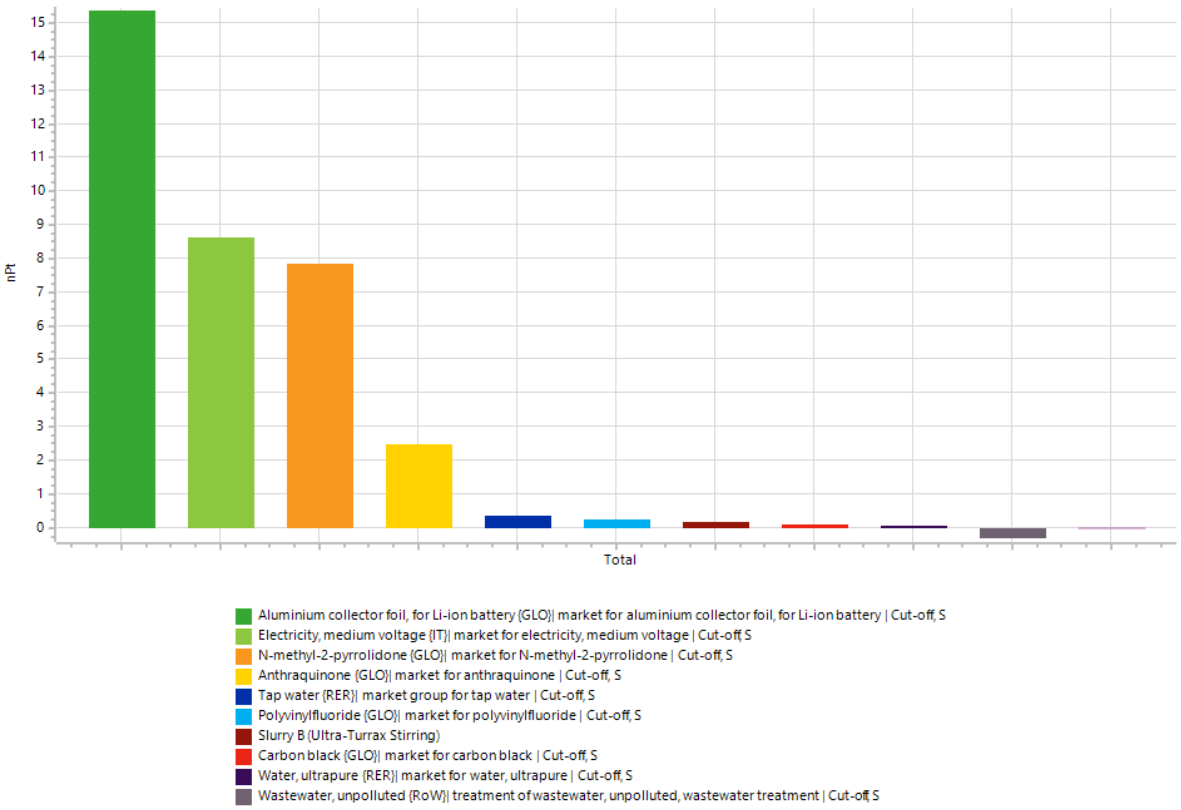

Figure 3: environmental impact in nPt for each input used in the production process of a 13.9 mg cathode.

Figure 4 shows the environmental contribution of each input, separated by the three most relevant impact categories affecting the cathode's life cycle.

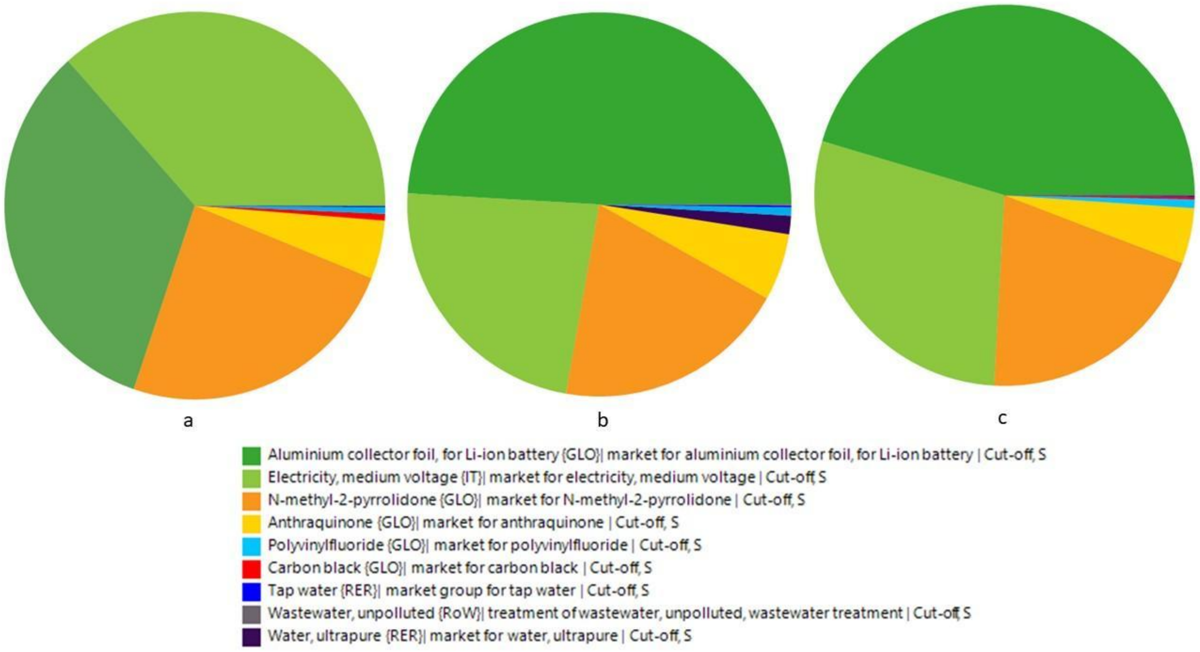

__Figure 4__: contribution in nPt of each input for the production of a 13.9 mg cathode, for the impact category "Resource use, fossil"(a), "Eutrophication, freshwater" (b), "Climate change" (c).

Finally, in **Figure 5**, a direct comparison between the green cathode studied here and a commercial NMC811 cathode, based on a normalized 1 mAh charge storage capacity, shows clear environmental advantages for the green option.

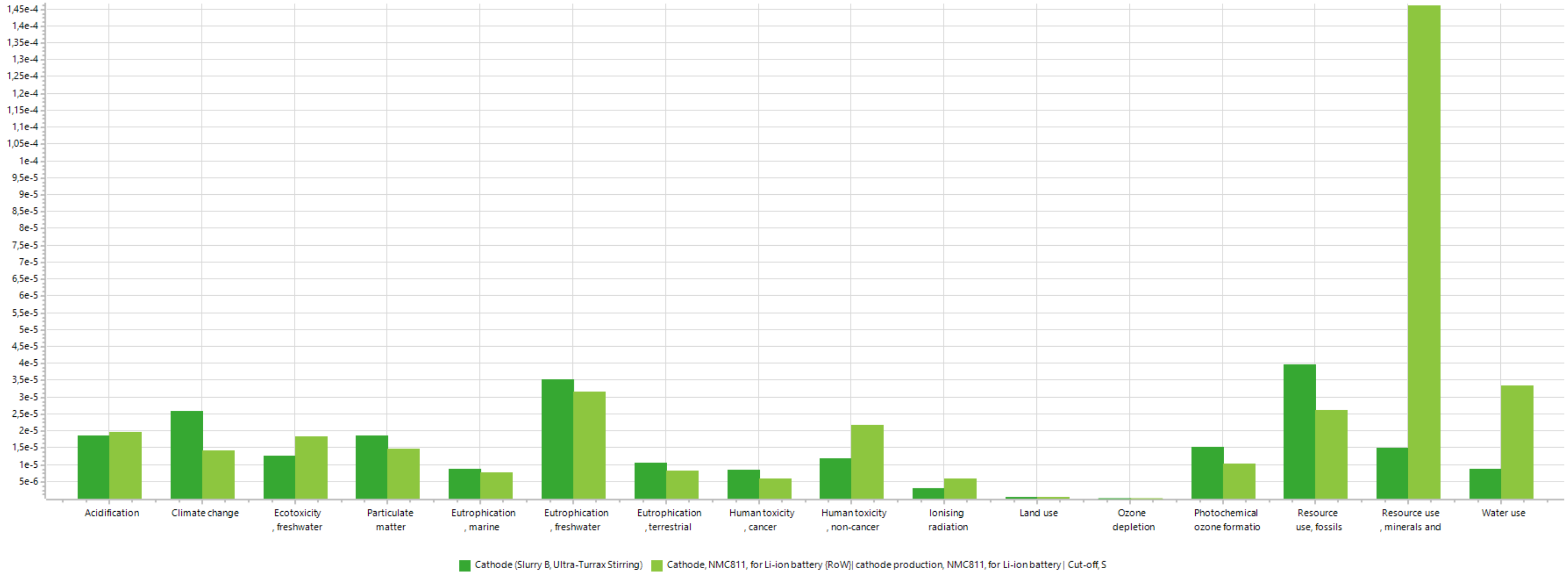

***Figure 5**: comparison, with normalized values, between green cathode and NMC811 cathode for each impact category.*

In particular, the green electrode performs much better in the category "*Resource Use, Minerals and Metals*", due to the absence of critical metals like nickel, manganese, and cobalt, which are widely used in conventional cathodes. Another important difference is in "*Water use*", which is significantly lower for the green system.

6. CONCLUSIONS

The LCA results, based on the EF 3.1 method, clearly show that the green electrode developed from agricultural waste has significantly lower environmental impacts overall compared to a conventional NMC811 cathode.

While some individual components (such as aluminium foil, NMP, and electricity consumption) still contribute noticeably to the environmental footprint of the new electrode, the absence of critical metals results in a major reduction in the "*Resource use, minerals and metals*" category. This is a key advantage, as the extraction and processing of metals like nickel, manganese, and cobalt in traditional cathodes are among the most impactful stages in battery production.

Moreover, when results are normalized to the same charge storage capacity (1 mAh), the total impact across most categories is consistently lower for the bio-based electrode. This includes not only "*Resource use*, *minerals and metals*", but also "*Water consumption"* and "*Human toxicity, non-cancer*". Although some categories still show comparable values, the results clearly indicate potential for further improvement, particularly using renewable electricity and more environmentally friendly solvents. These optimisations could reduce the remaining impacts. In conclusion, this study confirms that the bio-based electrode is not only a technically viable solution, but also a much more environmentally sustainable option. It represents a concrete step forward in reducing the ecological footprint of energy storage technologies and supports the transition toward greener, circular battery systems.