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Farm to cable: life cycle assessment of carbon electrocatalysts derived from coffee waste

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To realize the full potential of biomass waste-derived electrodes, their synthesis must be fully reproducible and their environmental life cycle impact must be assessed quantitatively. We now show how a systematic comparison of coffee waste as a source for direct hydrazine fuel cell anodes can inform the first full life cycle assessment (LCA) of this application. The result is a practical process yielding active and replicable materials, whose quantified environmental footprint points to actionable avenues for further development.

Although biomass contains enough carbon to replace fossil fuel as a chemical feedstock,¹ not all biomass-based processes are sustainable or able to yield reproducible products, given that the biomass feedstocks they treat vary in composition. Spent coffee waste, of which 6.5 million tons are produced globally each year,² is a case in point: although used as a source for solid carbon powders for purification,³ supercapacitors,⁴ batteries and fuel cells,⁵ it remains a poorly defined substance. Coffee is sourced from many geographies and processed by many methods, resulting in coffee-derived carbons with broad distributions of structures, chemical compositions, and ecological footprints. After consumption, spent coffee grounds can be treated as a waste or valorized to economic products like fuel, building materials, or used agricultural amendments.^{6–8} The treatment of spent coffee waste should be evaluated using a systematic environmental life cycle assessment (LCA) to understand preferred options for end-of-life (EoL) management. The reproducibility of biomass-derived carbons is especially important when designing fuel cell anodes, *e.g.* for

Sustainability spotlight

Coffee ground waste and other biomass resources could be promising sources of carbon and nitrogen for manufacturing anode catalysts for future fuel cells. Coupled with earth-abundant iron, such FeNC catalysts could reduce the use of critical raw materials like platinum, which are currently the primary materials for electrocatalysts. However, biowaste is an unpredictable precursor for precise electrodes, with varied composition and structure. Here we show how careful biowaste selection, together with prospective life cycle assessment focused on climate change impacts, can guide the design of advanced FeNC electrodes for direct hydrazine fuel cells. This material sources the carbon from coffee waste, thus recycling the biogenic carbon in the waste compared with composting or land-filling. We conclude that manufacturing FeNC catalysts from coffee and more generally, other bio-organic waste, can make progress towards meeting UN Sustainable Development Goals of climate action (SDG13) and affordable and clean energy (SDG7).

oxidizing hydrazine hydrate ($\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$),⁹ an energy dense (3.45 kWh L^{-1}),¹⁰ safe and transportable alternative to anhydrous hydrazine and compressed H_2 gas.¹¹ The hydrazine oxidation reaction ($\text{HzOR}, \text{N}_2\text{H}_4 + 4\text{OH}^- \rightarrow \text{N}_2 + 4\text{H}_2\text{O} + 4\text{e}^-$) has the highest known theoretical cell potential in O_2 -based fuel cells (1.56 V , *viz.* 1.23 V for H_2). However, the reaction overpotential strongly depends on the catalytic site, restricting the use of poorly reproducible biomass as a precursor.

Herein, we show how spent coffee waste obtained from a variety of sources can yield reproducible, high-value Fe- and N-doped carbon electrodes (FeNCs) for direct hydrazine fuel cell (DHFC) anodes. By performing a full cradle-to-gate LCA spanning from spent coffee waste collection to fuel cell utilization (Scheme 1), we quantify key environmental impacts of the process, compare them to commercial alternatives, conventional EoL treatments and outline actionable directions for further research and optimization to reduce global warming, toxicity and other environmental impacts. The case of coffee waste is therefore a model for all biowaste-to-electrode development processes. It highlights the importance of waste variety choice and the resulting environmental life cycle impact of the FeNC production process.

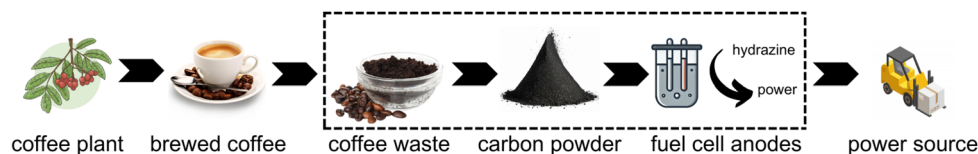
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Scheme 1 Production process and system boundaries (dotted line) of waste coffee-derived Fe–N–C electrocatalysts.

The FeNC powders were synthesized from six coffee waste samples collected from various sources in Israel (Table S1). The coffee waste samples were dried, ground and chemically activated by pyrolysis with K_2CO_3 at 800 °C.¹² These carbons ($\text{NC}_{\text{source}}$) were loaded with iron salts and phenanthroline ligands, which provide most N to the catalyst, and heated to 600 °C, yielding atomically dispersed Fe–N₄ moieties ($\text{FeNC}_{\text{source}}$).^{13–15} The carbons have multi-modal ('hierarchical') pore sizes, ranging from macropores (>50 nm) to micropores (<2 nm), as determined by scanning electron microscopy and N_2 sorption (Fig. 1). Their BET-derived specific surface areas (SSAs) are high at 1200–2200 $\text{m}^2 \text{g}^{-1}$, as are their electrochemical surface areas (80–230 $\text{m}^2 \text{g}^{-1}$, Fig. 1c). Both high surface area and multi-sized porosity enable fast flow of reactants to active sites during catalysis. The carbons are sufficiently graphitized, providing electronic conductivity, as testified by the Raman intensity ratio of disordered (D) and graphitic (G) bands, with $I_{\text{D}}/I_{\text{G}}$ values typical for successful electrocatalysts (Fig. S1 and Table S2).^{16–18}

The FeNC catalysts were electrocatalytically active towards hydrazine oxidation in 1 M KOH (Fig. 2a), with onset potentials ranging between 0.21 and 0.38 V vs. RHE. $\text{FeNC}_{\text{Nescafe}}$ and $\text{FeNC}_{\text{Nespresso}}$ showed earlier onsets than most known FeNC electrocatalysts for the HzOR (0.21–0.23 V vs. RHE).^{19,20} The synthesis of $\text{FeNC}_{\text{Nescafe}}$ was repeated in five batches to yield 0.2 g of $\text{FeNC}_{\text{Nescafe-mixed}}$. Its HzOR activity was compared to that of commercial FeNC from Pajarito Powder, USA ($\text{FeNC}_{\text{Pajarito}}$),²¹ showing similar performance in a lab-scale experiment (Fig. 2b). Moreover, when compared in a full platinum group

metal PGM-free direct hydrazine fuel cell, $\text{FeNC}_{\text{Nescafe-mixed}}$ anodes yielded higher open circuit voltages (OCV), higher peak power densities, and higher limiting current densities relative to $\text{FeNC}_{\text{Pajarito}}$ (Table S3).

To build on the promising electrocatalytic activity of the coffee-derived FeNC, as verified by fuel cell testing, LCA (ISO 14040/44)^{22,23} was applied to evaluate the production of the coffee-derived $\text{FeNC}_{\text{Nescafe-mixed}}$ electrocatalyst and to compare and benchmark its environmental performance with a functionally equivalent commercial electrocatalyst, $\text{FeNC}_{\text{Pajarito}}$, which relies on chemical sources of carbon and nitrogen (nicarbazin) rather than biomass. Both electrocatalysts were tested in a direct hydrazine fuel cell producing 1000 mW power. A previous LCA study was reported for $\text{FeNC}_{\text{Pajarito}}$ when used in an oxygen reducing PEM fuel cell cathode.²⁴ Another LCA exists for a biomass-derived FeNC used in Fischer–Tropsch thermal catalysis.²⁵ Using a cradle-to-gate system boundary, we evaluated three production scenarios: (i) lab-scale, as described above; (ii) optimized lab-scale, with improved coffee batch yield, oven energy efficiency, heating rates and atmosphere, and FeNC product yield relative to the lab-scale scenario; and (iii) pilot scale with high product yield. Life cycle inventories were built following laboratory scale-up methods²⁶ commonly used with laboratory data;^{27,28} the pilot scenario assumed the usage of renewable ethanol solvent with solvent recovery by distillation.^{29,30} To assess the environmental trade-offs of valorizing coffee waste into high-performance products, we also compared the treatment of 1 kg of coffee waste *via* three conventional EoL options: landfilling with energy recovery; composting; and

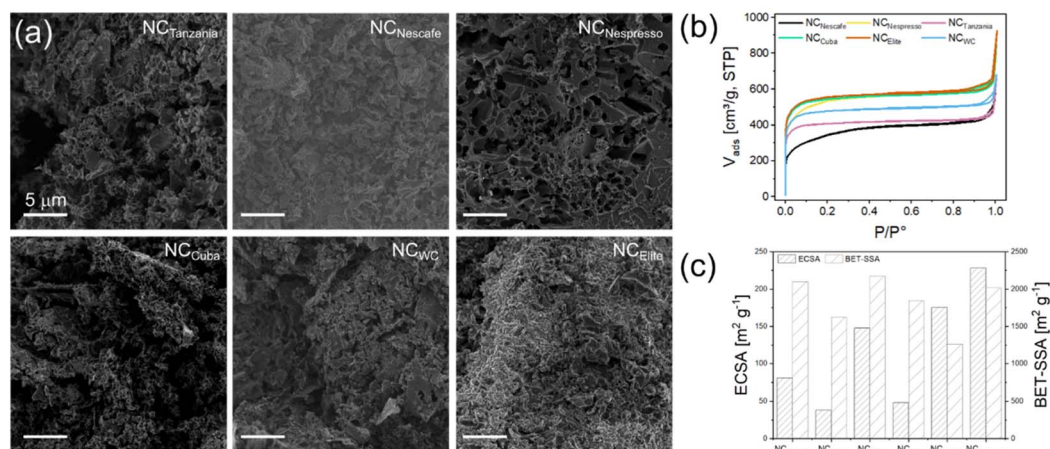
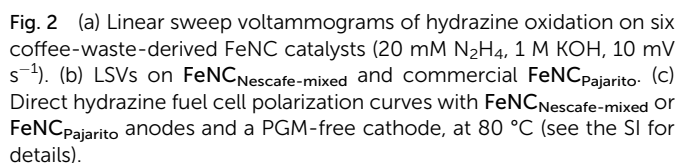


Fig. 1 (a) Characteristic scanning electron micrographs of the coffee-derived carbons. (b) N_2 sorption isotherms at 77 K. (c) Specific surface areas (SSAs-BET) and electrochemical surface areas (ECSAs) of the carbons.





A life cycle inventory (LCI) model was developed to account for the collection, transportation and processing of coffee waste and its conversion into an electrocatalyst in the system boundary (Scheme 1) in Europe, with the functional unit defined as the catalyst quantity needed to generate 1000 mW power (per DoE milestones)³⁴ to operate a hydrazine fuel cell. Background data used in the LCI model were taken from the ecoinvent v3.5 (ref. 35) database and modeled using SimaPro software.³⁶ The life cycle impact assessment method used to compare the scenarios applied the ReCiPe 2016 midpoint hierarchist method.³⁷ The fraction of stable (sequestered) organic C was estimated following calculations on CO₂ offset in biochar.³⁸ For the EoL scenarios, LCI data for landfilling and composting were obtained from previously published work by

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Fig. 3 GWI results for the production scenarios of lab scale **FeNC_{Nescafe-mixed}** (lab scenario), optimized scale (optimized scenario), pilot scale scenarios include consideration of no credit and a credit for avoided GHG emissions from diverting the spent coffee waste from composting, landfilling, or WtE treatment systems, and **FeNC_{Pajarito}** (commercial).

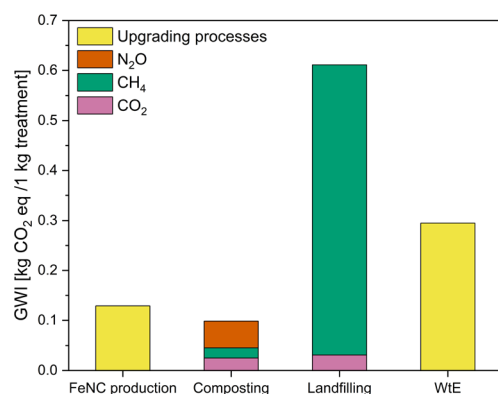
Fig. 4 reports the GWI for alternative treatments of spent coffee waste. The GWI values are expressed as emissions of CO₂, CH₄, and N₂O in CO₂ equivalents (CO₂eq) according to the 100-year GWP of each gas, where 1 g of CH₄ and 1 g of N₂O correspond to 28 g and 298 g CO₂eq, respectively.³³ Each scenario in Fig. 4 is presented using disaggregated or aggregated impact, depending on data availability. For landfilling and composting, detailed emission inventories were available, allowing for individual contributions of CO₂, CH₄, and N₂O; however, only aggregated data were available for the WtE. Thus, these are grouped under “upgrading processes” in the figure. Regarding the FeNC production process, disaggregated GWI results can be found in Fig. 3. Regarding the EoL options, the environmental impact of emissions associated with landfilling is closely linked with emissions of methane during the degradation of the waste under anaerobic conditions. Furthermore, emissions of NO_x

We conclude that alternative sources of coffee waste can be sequestered into functional FeNC electrocatalysts for a direct hydrazine fuel cell. Analyzing the life cycle environmental impact of these catalysts, relative to a commercial material, highlights the need for process optimization during scale-up, revealing benefits such as reducing landfill emissions, enhancing resource efficiency, and reducing the reliance on finite resources. Finally, we stress that any process developing biowaste into precise electrodes should take into account our findings regarding the coffee waste-derived electrocatalysts; that a precise and well-reported choice of waste precursor (type and region) has a huge effect on performance; and that a full LCA offers actionable directions for further development.

STA initiated the collaboration and was responsible for conceptualizing the catalysts' research methodology, synthesized, tested, and characterized the catalysts (with SB), and with AS developed the LCA research methodology. AS performed life cycle assessment, SMZ performed fuel cell experiments (supervised by DRD), STA and AS wrote the original manuscript, and TKS analyzed oven power. SS and DE supervised the project and edited the manuscript.

There are no conflicts to declare.

The data supporting this article have been included as part of the SI. See DOI: <https://doi.org/10.1039/d5su00618j>.



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