A Hybrid LCA Framework for Drug-Level Carbon Footprint Assessment Under Data Constraints: Application to Narrower-Spectrum Penicillin

Topic: Methodological advances in extending input-output databases: sectoral disaggregation, matrix augmentation, and hybrid approaches
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Understanding drug-specific carbon footprints is increasingly important as healthcare sustainability and product-level reporting gain prominence in regulatory initiatives, such as corporate sustainability reporting and digital product passports, yet such estimates remain largely unavailable due to sparse drug-level data. The research question of this study, therefore, consists of two components: How can drug-specific carbon footprints be estimated under data scarcity, and what additional insights does such disaggregation provide compared to sector-level pharmaceutical accounting?

We develop and demonstrate an MA-based hybrid LCA framework under data-limited conditions to disaggregate narrow- and medium-spectrum penicillin from the aggregated pharmaceutical sector in the ICIO-2023 EE-MRIO to enable the calculation of the penicillin carbon footprint across countries. The data-limitations refer to unavailable total output values, basic prices, sales data, and incomplete physical life cycle inventory. The MA is implemented in three steps. First, we derive annual final consumption of penicillin in monetary terms by converting physical use data and estimating country-level prices that maintain the fundamental input-output monetary balances, and we allocate the resulting penicillin consumption between domestic and imported sources based on ICIO-2023. Second, we construct a monetary unit process for penicillin based on a detailed physical LCI, applying country-specific prices; this yields monetary input coefficients that reflect cross-country price variation rather than differences in underlying physical production technology. Third, we integrate the resulting penicillin final consumption and production unit process into ICIO-2023, generating penicillin-specific production inputs, output distribution, and direct emission intensities consistent with the MRIO accounting principles. Lastly, the structured uncertainty assessment evaluates how key assumptions required to conduct MA affect footprint estimates. We document all data gaps and corresponding modelling choices, classify them by type and expected influence, and conduct scenario-based robustness tests targeting major sources of uncertainty.

We used ICIO-2023, the latest EE-MRIO from the OECD that includes 45 sectors, 77 regions, among which one rest-of-the-world region, and emission accounts. The database runs until 2020; we focused on 2019 to exclude the year affected by COVID-19 (2020). The production recipe of penicillin is based on the LCA study by Harding et al., because of its detailed documentation of both economic and environmental flows. Furthermore, we used the yearly narrow- and medium-spectrum penicillin consumption data in daily defined doses (DDD) from the global antibiotic consumption study of Klein et al, which reports 56 of the 77 countries in ICIO-2023, to construct the final consumption matrix. We used the DDD quantity of penicillin as defined by the WHO. Lastly, income group classification and population size were based on World Bank data.
Furthermore, we estimated the penicillin consumption of the missing countries using their population size and the average per capita penicillin consumption of the countryâ€™s income group according to the World Bank classification. For converting consumption and LCA data into monetary units, we used export prices calculated from the latest available BACI trade dataset as a proxy. BACI does not report prices for water, electricity, or heat, and country-specific data for these were difficult to obtain; we assumed uniform prices across countries, based on ecoinvent and Eurostat. Furthermore, BACI was also used to construct a sourcing pattern for penicillin consumption.

This work makes three contributions. First, we develop a systematic and reproducible framework for applying MA under data-limited conditions that is designed to be transferable as more drug-level LCIs and international statistics become available. Second, we demonstrate the framework using penicillin and provide, to our knowledge, the first consistent global estimate of a drug-level carbon footprint across countries. We estimate its global consumption in 2019 to be about kt COâ‚‚e. Although modest in magnitude, the footprintâ€™s geographic distribution differs markedly from that of aggregated pharmaceuticals, showing that sector-level accounting can mask substantial cross-country heterogeneity. Across alternative assumptions, global totals vary by less than 30%, and country rankings remain largely stable, indicating that the observed patterns reflect structural differences in consumption and sourcing rather than artefacts of specific modelling choices. Lastly, our uncertainty assessment highlights priority data and modelling gaps that, if addressed, would both improve the accuracy of product-level carbon footprints and enable coverage of a broader range of pharmaceuticals.