Bio-Based Arabinoic Acid Production via Catalytic Arabinose Oxidation: A Green Chemistry Route Evaluated by Life Cycle Assessment

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Highlights

- Bio-based arabinose oxidation demonstrates inherently low direct carbon emissions vs. fossil routes
- Sodium hydroxide production and fossil energy emerge as primary environmental barriers, not catalysis
- LCA-guided process design enables rapid identification of climate-mitigation intervention points.

1. Introduction

Production of fine chemicals from bio-derived feedstocks is a critical pathway toward climate-neutral chemistry. Arabinoic acid (a C5 polyhydroxy carboxylic acid used in polymers and pharmaceuticals) is conventionally synthesized via energy-intensive fossil-based routes. This work evaluates whether catalytic oxidation of arabinose — abundant in lignocellulosic streams — provides an economically viable and environmentally superior alternative. Using Life Cycle Assessment, we identify process-level barriers to achieving climate-change mitigation.

2. Methods

A scaled-up catalytic sugar oxidation process was modeled base on the flowsheet displayed in Figure 1. The model implemented in Aspen Plus v14 incorporated experimentally confirmed kinetic models, transport phenomena and component mass balances. The environmental performance of the proposed concept was assessed via cradle-to-gate LCA (SimaPro v10.1, IMPACT 2002+ V2.15 methodology) with functional unit of 1 kg arabinoic acid solution (30 wt%). Four foreground flows were modeled: arabinoic acid solution, NaOH (chlor-alkali production mix), steam heat (MJ), and grid electricity (kWh). Background data (electricity, steam, chemicals) used ecoinvent v3.8 European average datasets.

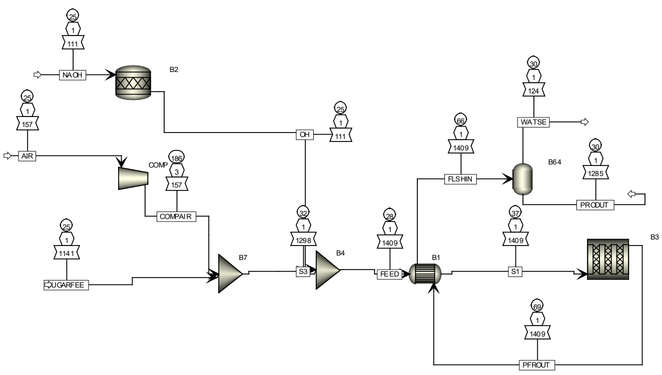

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Figure 1. Process flowsheet of industrial scale arabinose oxidation implemented in Aspen Plus software.

3. Results and discussion

Figure 2 displays the characterization across 15 impact categories. Human toxicity (carcinogenic and non-carcinogenic effects) dominates, driven by sodium hydroxide production (chlor-alkali process) and wastewater treatment — revealing the bottleneck lies in auxiliary chemicals, not in catalysis. Respiratory inorganics shows highest absolute impact, almost entirely from heat/steam, indicating that the energy intensity is the primary operational driver.

The climate change (called global warming in Europe) contribution to this process is moderate and distributed across thermal and electrical energy consumption. Critically, this technology is far lower than fossil routes, confirming the catalytic bio-based chemistry carries inherently low direct carbon footprint — climate impacts are supply-chain mediated, not reaction-intrinsic. Resource depletion follows energy and NaOH profiles, again pointing to the supply-chain choices. Ionizing radiation shows a net negative value (environmental credit) from bio-based sourcing. Ozone depletion, acidification, and photochemical ozone formation are negligible in this process.

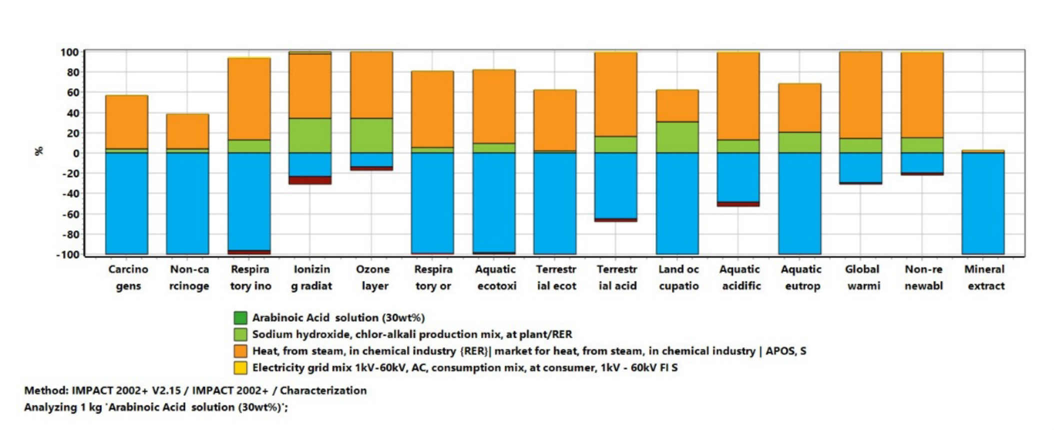

Figure 2. LCA characterization results (IMPACT 2002+ V2.15) for arabinoic acid production via catalytic arabinose oxidation. Impact categories (x-axis) vs. environmental impact units (y-axis). Four contributors shown: arabinoic acid solution (blue); sodium hydroxide chlor-alkali production mix (green); heat from steam in chemical industry (orange); grid electricity consumption (yellow)

4. Conclusions

Catalytic arabinose oxidation offers a bio-based route with inherently favorable environmental profile. Major burdens — human toxicity, respiratory impacts, resource depletion — originate from auxiliary inputs (NaOH) and fossil energy, not the catalytic reaction. This approach validates the green chemistry merit and reveals three directly addressable interventions:

1. Replace chlor-alkali NaOH with membrane-based electrolysis
2. Integrate renewable thermal energy (solar, biomass steam, waste heat)
3. Source grid electricity from renewable sources

These improvements substantially reduce the environmental footprint and accelerate future transition to climate-neutral fine chemical production in the biorefinery context. The LCA framework provides a replicable methodology for identifying environmental hotspots in emerging catalytic processes

Keywords
LCA; Biomass; Ecoinvent; Simapro