



Environmental impacts of sugarcane wax biorefining via Swenson process: a life cycle perspective with regional analysis of energy advantages

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Abstract

A significant opportunity to mitigate environmental impacts in the sugarcane (*Saccharum officinarum* L.) industry lies in quasi-circular biorefinery routes, such as the Swenson Process (SP), which employs sustainable methods for raw wax extraction, where careful solvent selection and regional energy matrix choices are crucial. This study conducts a Life Cycle Assessment (LCA) of the SP, focusing on two key aspects: (1) Comparative energy advantages in Northeast Brazil versus Cuba (Global Warming Potential over a 100-year timescale - GWP-100). (2) Environmental impact assessment of heptane-based extraction versus toluene-based alternatives, selected using Hansen Solubility Parameters in Practice (HSPiP[®]) software database. The LCA was conducted using openLCA[®] software and Ecoinvent[®] database, monitoring 16 input and output variables in a production flow processing 15 t/h of filter cake to produce 5.54 t/d and 4.95 t/d of raw wax using heptane and toluene, respectively. Monte Carlo simulations indicate that the total GWP-100 of the SP is $(9.6 \pm 2.8) \times 10^3$ and $(11.0 \pm 3.4) \times 10^3$ kg CO₂ eq/t raw wax for heptane and toluene, respectively, in Cuba, while for Brazil these values decrease to $(4.9 \pm 1.3) \times 10^3$ and $(6.1 \pm 1.8) \times 10^3$ kg CO₂ eq/t raw wax, respectively. The analysis also revealed that while heptane showed no significant toxicity risks, toluene exhibited measurable human non-cancer toxicity effects. The lower GWP-100 impact estimated for Brazil versus Cuba, primarily due to differences in electricity grid composition, suggests significant environmental benefits for implementing this technology in this leading sugarcane-producing country. These findings provide valuable guidance for the sustainable development of sugarcane biorefineries and contribute to understanding environmental considerations in SP.

Keywords Swenson process · Regional energy advantages · Environmental impacts of solvents · Hansen solubility parameters · Filter cake valorization · Uncertainty assessment

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Introduction

Sugarcane (*Saccharum officinarum* L.) occupies a prominent position in global agriculture [1]. With cultivation spanning more than 26 million hectares and production exceeding 1,922 million tonnes, it plays a particularly significant role in the Brazilian economy, with the country accounting for 38% of world production in 2022 [2].

Globally, sugarcane processing to obtain sugar and/or ethanol generates more than 280 million tonnes of waste and by-products annually, including straw, bagasse, filter cake (also known as sugarcane mud or press cake), wastewater, ash from bagasse incineration, vinasse from ethanol distillation, and molasses [3, 4]. The sustainable management and valorization of this biomass present significant opportunities for developing integrated biorefineries aligned with circular economy principles [5].

Biorefineries offer a compelling alternative to traditional production processes, optimizing resource efficiency and fostering a more sustainable approach to manufacturing [6]. Within this context, raw cane wax stands out as a high-value bioproduct with growing market potential [7]. Extracted from filter cake [8], raw cane wax has diverse applications across pharmaceutical, agronomic, nutraceutical, and cosmetic industries [9–11].

To reduce the negative impacts of the production cycle and improve the efficiency of raw cane wax production practices, a comprehensive understanding of its environmental impact is fundamental. Life Cycle Assessment (LCA) provides a powerful framework for this analysis, as it evaluates the full spectrum of environmental burdens associated with a product or process, from raw material extraction to end-of-life considerations. While other processes related to the sugarcane industry have been assessed in the literature [10, 12–32], the LCA of raw cane wax extraction remains largely unexplored.

This study addresses this knowledge gap by conducting a detailed LCA of the liquid-liquid extraction process for raw cane wax based on heptane as a solvent, exploring possible alternative solvents, and analyzing regional energy advantages comparing Cuba with Brazil. Specifically, because the incumbent solvent (heptane) is fossil-derived and inevitably subject to evaporative losses during operation, evaluating alternative solvents aligns with green chemistry principles and offers a pathway to potentially reduce both toxicity and carbon footprint.

Based on these gaps, we formulate two working hypotheses: (H1) among the candidate solvents identified through Hansen Solubility Parameters, the currently used heptane might not be the environmentally optimal option, and (H2) implementing the Swenson process in Brazil, with its lower-carbon electricity mix, would substantially reduce the

GWP100 of raw wax production compared with the Cuban case. Hypothesis 1 is explicitly treated as exploratory, as a full environmental screening of all candidate solvents is beyond the scope of the present study.

This work represents the first fully parameterized Life Cycle Assessment (LCA) of the Swenson process for sugarcane wax extraction, integrating operational data, solvent-selection criteria based on Hansen Solubility Parameters (HSP), and a regional comparison involving uncertainty propagation. While LCAs of sugarcane-related systems are available (including ethanol production, bagasse valorization, biogas generation, and integrated biorefineries), none have addressed wax extraction, solvent-route differentiation, or the implications of molecular affinity on environmental burdens. This study, therefore, fills an important gap in the environmental assessment of sugarcane biorefineries.

Through this comprehensive assessment, this research aims to contribute towards the development of more sustainable and environmentally conscious approaches to raw cane wax production within the broader context of sugarcane biorefinery optimization.

Materials and methods

Process description and operating parameters

The extraction of raw cane wax was analyzed based on the process implemented at a Cuban biorefinery located in Majibacoa (Las Tunas, Cuba), which utilizes the Swenson method [33] (Fig. 1). The Swenson process refers to a patented counter-current solvent extraction approach originally developed for recovering wax from sugar-mill filter press cake (“cachaza”). Industrial implementation has been reported mainly in Cuba, where dedicated raw-wax facilities based on the Swenson process have been described in the technical literature. Publicly available sources do not provide a consistent quantitative estimate of the technology’s share relative to other wax-recovery routes; therefore, this study treats the Swenson process as a case-study technology parameterized from the Majibacoa facility and uses the Brazilian scenario as a prospective (non-existing) implementation for regional electricity-mix comparison.

The process begins with filter cake, a residue generated during cane juice clarification that constitutes approximately 17% of the total processing waste [8]. Filter cake, rich in palmitic and linoleic acids, undergoes a controlled extraction process in a specially designed extraction column.

The extraction system operates through the following sequence: filter cake is introduced through the top of the extraction column after its fluidity is verified using a consistency gauge. Within the column, the material flows

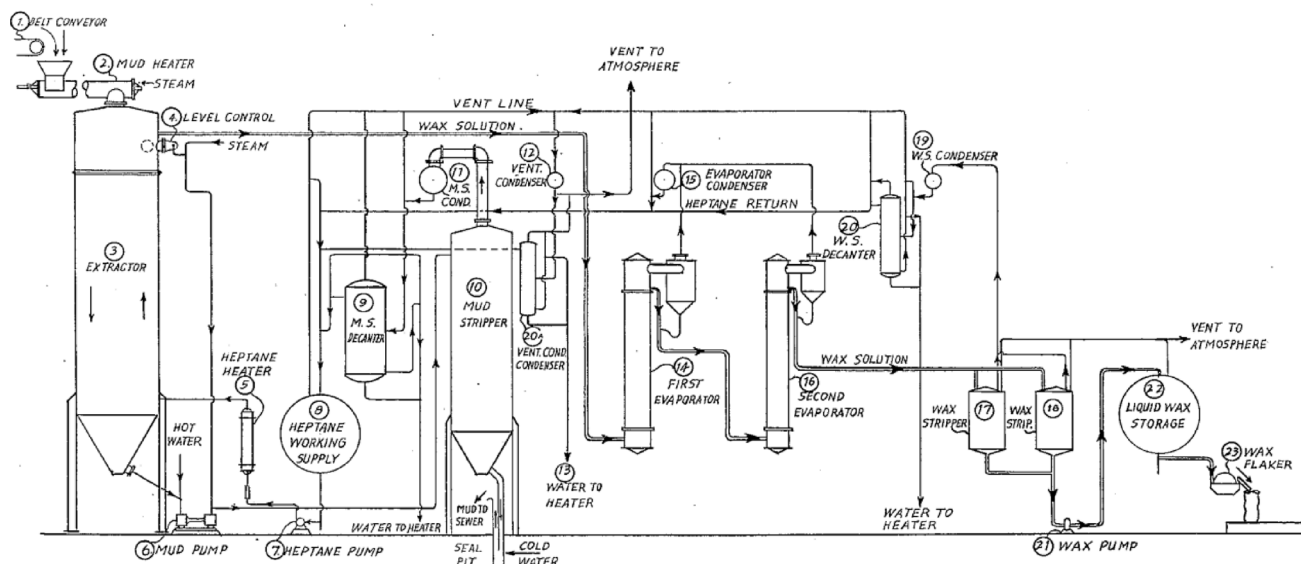


Fig. 1 Swenson raw wax biorefining process [33]

downward through a series of horizontally arranged perforated plates. These plates feature central openings that create an alternating flow pattern between the center and periphery, with downward-facing edges directing the flow. Continuous agitation is maintained by metallic arms fixed to a central axis.

Operating in a counter-current configuration, the heated solvent is injected at two points below the lowest tray in the thermally insulated extractor. The solvent flow rate is regulated by an automatic valve to maintain optimal extraction conditions. The wax-solvent extract rises above the filter cake level in the extractor and passes through a sieve that retains pith and small filter cake particles.

The filtered extract flows by overflow into a collector that channels it to a washing tank, followed by processing in a falling film evaporator for concentration. The concentrated extract then enters purifiers for final solvent removal before the melted wax is packaged in multilayer paper bags, where it solidifies. A patented continuous vapor separator achieves high efficiency in separating the solvent from the filter cake extracted from the extractor. The water-solvent mixture undergoes decantation to recover the solvent for reuse in the process.

The process operates with a 2.48% loss rate of heptane. The solvent's thermal properties are characterized by a heat of vaporization of 318.00 kJ/kg and a specific heat of 2.24 kJ/kg·°C. The liquid filter cake discharge (6 to 8% solid content) from the recovery unit constitutes the process's residual liquid stream.

Initially, the liquid filter cake was discharged into drainage ditches at the Central Azucarero Majibacoa plant under its previous North American ownership. Since the 1990s,

this residual stream has been repurposed for sugarcane field irrigation and distributed using a system of pipes and tractors.

Solvent selection and analysis

The Swenson process's inherent heptane losses through volatilization prompted an investigation into alternative solvents based on physicochemical criteria. Recent studies have focused on determining Hansen solubility parameters (HSPs) of sugarcane wax fractions to identify optimal solvents for each component [10, 32, 34–36].

For implementation in the Swenson process, alternative solvents must meet several critical criteria. Candidate solvents were screened using Hansen Solubility Parameters (HSP) for wax fractions (R_a , RED, and R_0), requiring high affinity ($R_a/R_0 < 1$), density lower than water, low solubility in water ($\log S < -1$), and a boiling point compatible with the operating temperature of the Swenson extractor and evaporator. Additional constraints included safety considerations, compatibility with existing equipment, and prior evidence of extraction performance in laboratory studies for sugarcane wax and cuticle lipids. The solvent density must be lower than that of water to enable extraction through the column top while maintaining minimal water solubility. Additionally, solvents must demonstrate high affinity with wax, indicated by actual solute-solvent distance (R_a) and Hansen sphere radius (R_0) values ($RED < 1$). Furthermore, the solvent should have a relatively low boiling point to minimize energy requirements during recovery.

Table 1 presents relevant properties of heptane and potential alternative solvents, identified using the Hansen

Table 1 Relevant properties of heptane and suggested alternative solvents suitable for the Swenson sugarcane raw wax extraction process

Solvent	RER	R_a	RED	Extract. yield (%)	Density (kg·m ⁻³)	Boiling point (K)	Flash point (K)	Melting point (K)	Log S
Heptane	390	5.84	1.54	5.6–5.8*	684	371	269	182	−3.65
Cyclohexane	560	3.74	0.98	1.2 [36]	779	354	255	280	−2.25
Dimethyl cyclohexane	125	4.45	1.17	—	784	393	289	240	−3.21
D-Limonene	25	2.65	0.70	—	839	450	316	199	−3.00
Ektasolve EEH	0.3	5.23	1.38	—	893	503	379	223	−3.70
Hexane	830	6.50	1.71	5.3–5.7 [38]	659	342	250	178	−2.87
Methylcyclohexane	300	4.45	1.17	—	769	374	269	146	−2.80
Methyl oleate	0	3.96	1.04	—	870	617	453	293	−4.53
Ethyl benzene	89	2.28	0.60	—	867	409	293	178	−1.78
Toluene	190	1.54	0.40	5.4–5.6 [39] 11.6–14.6 [40]	867	384	277	178	−1.27
Xylene	80	2.09	0.55	5.9 [36]	861	413	297	258	−1.70
Isobutyl isobutyrate	43	6.36	1.67	—	862	421	311	192	−1.24
Fatty acid methyl ester	0.2	3.54	0.93	—	860	617	453	293	−4.53
p-Cymene	13	0.80	0.21	—	857	457	—	225	−2.50
Solvesso 100	16	1.98	0.52	—	880	423	322	258	−3.89
Solvesso 150	5	2.28	0.60	—	886	433	337	258	−3.82
VM&P naphtha	1000	6.50	1.71	—	740	359	278	193	−4.00

RER, R_a , and RED stand for relative evaporation rate vs. *n*-Butyl acetate, actual solute-solvent distance, and relative energy difference RED was computed as $RED = R_a / R_0$, using a Hansen sphere radius (R_0) of 3.80 for refined sugarcane wax. No R_0 is currently reported for crude wax; therefore, Table 1 RED values should be interpreted as a screening indicator based on refined wax. *: Records from the factory.

Solubility Parameters in Practice (HSPiP[®]) software database [37].

However, Table 1 shows that published data on extraction yields are unavailable for most candidate solvents identified by Hansen screening. Therefore, the solvent shortlist was further refined using laboratory evidence [36] together with Swenson-process operating constraints. Among the solvents evaluated for cuticle-wax extraction (o-xylene, toluene, ethanol, cyclohexane, and hexane), ethanol was excluded due to its water miscibility. Hexane was also excluded because its boiling point falls below the wax melting temperature (approximately 353 K), which would hinder liquid-phase extraction under Swenson conditions.

The remaining candidates (o-xylene, toluene, and cyclohexane) warranted further investigation. For the incumbent solvent, heptane, industrial records indicate an extraction efficiency of 5.6–5.8% raw wax in filter cake, whereas toluene achieves 5.4–5.6% [39], consistent with laboratory-scale studies using aromatic solvents. Because toluene also exhibited high extraction yields in the available laboratory studies [38, 39], it was selected for comparative LCA against heptane.

Although Hansen screening ($RED = R_a / R_0$) may classify heptane as a weak solvent when R_0 values reported for refined wax are applied, plant operation indicates that heptane can still be effective for extracting crude sugarcane wax from filter cake. This discrepancy is plausibly explained by three factors: (i) crude wax is a chemically diverse and variable multi-component mixture (dependent on cultivar and

processing conditions), (ii) Hansen parameters describe relative affinity rather than providing a direct solubility value, and (iii) an experimentally derived R_0 for crude wax is not available, so RED values necessarily rely on proxy fractions. Because published R_0 values differ markedly across related fractions (e.g., 3.80 for refined wax versus 10.8 for the oil fraction), crude wax—compositionally intermediate—may exhibit a larger effective R_0 such that heptane falls within the solubility sphere. Finally, Swenson extraction is performed above ambient temperature, which increases solubility and can further reconcile Hansen-based screening with observed industrial performance.

Process flow analysis and variable characterization

Table 2 delineates the key flow variables in the Swenson biorefining process through two alternative routes: route 1 using heptane as a solvent and route 2 using toluene. The process outputs are indicated in bold typeface, with X13 representing the primary product (raw wax). Daily production capacity reaches 5.54 tonnes and 4.95 tonnes for routes 1 and 2, respectively.

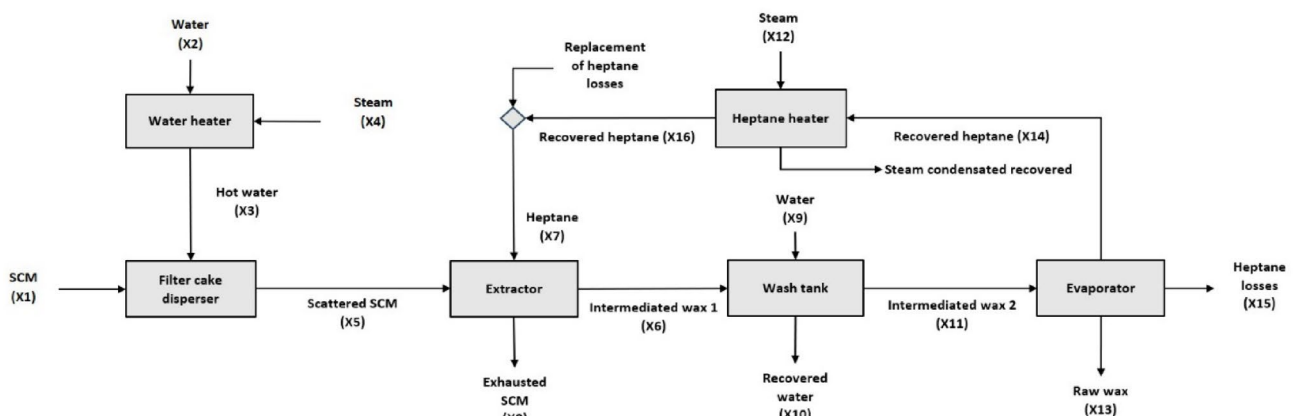
The process flow data summarized in Table 2 were derived from verified operational records of the Majibacoa facility, complemented by engineering design reports and mass and energy balance. Flow rates for steam, electricity, and solvent were obtained during plant visits and technical consultations with the production manager, while wax

Table 2 Alternative flows to raw wax extraction by the Swenson process

Component	Name	Flow	
		Route 1 - Heptane	Route 2 - Toluene
X0	Electric Power	1.6×10^3 kWh/t	
X1	filter cake	15 t/h	
X2	Water	10 t/h	
X3	Hot water	10 t/h	
X4	Steam	0.979 t/h	
X5	Scattered filter cake	25 t/h	
X6	Wax solution in solvent	14.368 t/h	18.213 t/h
X7	Solvent (Heptane or Toluene)	14.368 t/h	18.213 t/h
X8	Filter cake exhausted 1	25 t/h	
X9	Water	3.592 t/h	4.553 t/h
X10	Recovered water	3.592 t/h	4.553 t/h
X11	Intermediate wax 2	14.368 t/h	18.213 t/h
X12	Recovered steam condensate	2.368 t/h	
X13	Raw wax	0.231 t/h	0.206 t/h
X14	Solvent recovered (heptane or toluene)	13.953 t/h	17.772 t/h
X15	Solvent losses (heptane or toluene)	0.185 t/h	0.235 t/h
X16	Solvent Heated (recovered heptane or toluene)	13.953 t/h	17.772 t/h

yields and filter cake characteristics were validated against published studies on sugarcane mud processing [38–40].

Figure 2 illustrates the process stages, flows, inputs, and outputs with their corresponding quantities for route 1. The biorefining route 2, which employs toluene, follows a similar flow diagram with quantitative adjustments to inputs and outputs as detailed in Table 2.

**Fig. 2** Swenson process flow diagram for route 1 (using heptane as solvent), illustrating internal recirculation of solvent (X14), recovered steam condensate, and system outputs (raw wax X13 and solvent losses X15)

Life cycle assessment methodology and uncertainty analysis

The LCA was conducted in accordance with ISO 14040:2006 and ISO 14044:2006 standards. The analysis utilized openLCA[®] software (version 2.1.0) and Ecoinvent[®] database (version 3.6), incorporating uncertainty assessments with one million interactions, $1e-10$ cutoff line, and the Intergovernmental Panel on Climate Change (IPCC) 2021 impact assessment method.

The functional unit (FU) was defined as 1 tonne of raw cane wax produced at the factory gate. The system boundary extends from the reception of filter cake at the Swenson extraction unit to the production of raw wax, including solvent extraction, evaporation, solvent recovery, purification, and internal recirculation of water and solvent. Upstream processes such as electricity generation, steam production, solvent production, and rainwater harvesting are included through Ecoinvent[®] background datasets. Transportation and packaging are excluded, as discussed in Sect. 4.2. The impact assessment focuses on climate change (GWP100, IPCC 2021) and toxicity (USEtox[®] 2), which are the categories most sensitive to solvent choice and regional differences in the electricity mix.

The initial LCA focused on the Cuban biorefinery, where full-scale process data were available. A subsequent comparative analysis examined potential implementation in Bahia state, northeastern Brazil, maintaining identical physical production relationships. The regional analysis presented certain limitations within the Ecoinvent[®] database, which lacks comprehensive supplier information for all countries and regions. While openLCA[®] software provides calculation options with Global (GLO) or Rest-of-World (RoW) suppliers, Brazil benefits from some regionally disaggregated data, such as electricity supply information, enabling more precise analysis. For Cuba, although openLCA[®] supports

Table 3 Inputs for the Swenson process with heptane and toluene in Brazil and Cuba

Flow	Category	Amount	Unit	SD _g		Provider	
				Route 1	Route 2	Brazil	Cuba
(X0) Electricity, low voltage (both routes)	D: Electricity, gas, steam, and air conditioning supply/35.	1.6×10^3	kWh/t	373.258	411.026	Market for electricity, low voltage electricity, low voltage Cutoff, U-BR-North-eastern grid	Market for electricity, low voltage electricity, low voltage electricity, low voltage electricity, low voltage Cutoff, U-CU
(X1) Filter cake, from sugarcane juice filtration (both routes)	A: Support activities to agriculture and post-harvest crop activities/0161.	15	t/h	3.499	3.853	Market for filter cake, from sugarcane juice filtration filter cake, from sugarcane juice filtration Cutoff, U-GLO	
(X15) heptane losses (net solvent replacement)	C: Manufacture of refined petroleum products/1920.	0.185	t/h	0.043	0.048	Market for heptane heptane Cutoff, U - GLO	
(X15) toluene losses (net solvent replacement)	C: Manufacture of basic chemicals.	0.235	t/h	0.055	0.060	Market for toluene, liquid toluene, liquid Cutoff, U - RoW	
(X4) Steam, in the chemical industry (both routes)	C: Manufacture of basic chemicals.	0.979	t/h	0.228	0.251	Steam production, in chemical industry steam, in chemical industry Cutoff, U - RoW	
(X2+X9 – X10) Water, harvested from rainwater (both routes)*	E: Water collection, treatment, and supply/360.	6.408	t/h	1.495	1.646	Rainwater harvesting water, harvested from rainwater Cutoff, U - GLO	

* In these simulations, the same amount of water was used in both routes, for analytical simplification, as it caused the lowest relative impact according to the tests.

nationalized analyses, the database lacks information about regional suppliers of electricity and other variables, generating concrete but potentially less locally representative results [41]. Similar limitations apply to most suppliers in the Brazilian LCA, necessitating careful interpretation of the generated values.

Information quality and uncertainties were influenced by multiple factors, including cane variety, climate conditions, harvesting methods, juice extraction parameters, and other operational variables. Monte Carlo simulations with 5,000 iterations were performed to propagate inventory uncertainty, as sensitivity tests indicated that confidence intervals and scenario rankings became stable beyond approximately 4,000 iterations, while additional iterations would markedly increase computation time without improving the robustness of results. The analysis employed logarithmic normal distributions to evaluate uncertainties (Appendix A), with the geometric mean derived from measured point values and the geometric standard deviation (SD_g) calculated as the square root of the combined uncertainty from the Pedigree Matrix and basic uncertainty for each variable. This openLCA[®] configuration provides uncertainty indices in variance form, determined through the data quality matrix

Table 4 Outputs of the Swenson process

Flow	Category	Amount	Unit	SD _g
(X13) Raw cane wax (Route 1, extraction using heptane)	Support activities for crop production.	0.231	t/h	0.054
(X13) Raw cane wax (Route 2, extraction using toluene)	Support activities for crop production.	0.206	t/h	0.053
(X15) heptane (Route 1)	Elementary flows/ Emission to air/low population density	0.185	t/h	0.043
(X15) toluene (Route 2)	Elementary flows/ Emission to air/low population density	0.235	t/h	0.060

[31, 42]. Pedigree Matrix uncertainty indices, indicators, and scores are presented in Appendix B.

Tables 3 and 4 categorize system flows, presenting averages, geometric standard deviations (or combined uncertainty), and regionally identified suppliers. Several variables from Table 2 are omitted from Tables 3 and 4 as they represent intermediate flows. The inventory input values correspond to post-initial batches, accounting for the recycling of inputs such as solvent and water, with losses subtracted.

Outputs reused internally or externally are excluded from the inventory as their impacts are already subtracted as co-products, though they could alternatively be represented as avoided products with subtracted impacts.

The identical geometric mean values reported for several flows in Table 3 reflect the assumption of unchanged operating conditions across all scenarios. The only systematic difference between routes concerns the amount and type of solvent used and lost, whereas electricity, steam, and water use are assumed to follow the same physical relationships observed in the Cuban plant.

The Pedigree Matrix indices for route 1 variables followed the sequence (1; 4; 5; 1; 1), reflecting data quality characteristics verified during facility inspection and technical analysis with the general production manager: verified measurement-based data (U1 Reliability=1); market-relevant company representative data (U2 Completeness=1.10); data age exceeding 15 years (U3 Temporal correlation=1.5); study area specificity (U4 Geographical correlation=1); and enterprise-specific process and materials data (U5 Further technological correlation=1) [30, 31, 42]. Route 2 calculations employed modified indices (4; 4; 5; 1; 1), with U1 Reliability=4 representing industrial expert-qualified estimates based on laboratory experiments. A basic uncertainty index of 1.05 was applied for elementary flows, including thermal energy, electricity, semi-finished products, processed materials, and waste treatment services. The combined uncertainty indices (incorporating basic and

additional uncertainties) were 1.2 and 1.3 for routes 1 and 2, respectively.

Greenhouse gas emission factors for electricity, steam, and solvent production were taken directly from Ecoinvent[®] 3.6 and cannot be reproduced here in numerical form due to database licensing restrictions. Nonetheless, the relevant datasets (e.g., low-voltage electricity for Brazil's North-eastern grid and Cuba, steam production in the chemical industry, and global markets for heptane and toluene) are explicitly identified in Tables 3 and 5.

Results

Environmental impact categories assessment

Toxicity Impacts

The USEtox[®] 2 (recommended+interim) toxicity impact analysis examined three sub-groups: freshwater ecotoxicity, human toxicity cancer, and human toxicity non-cancer. For heptane, no significant toxicity values were detected in the USEtox[®] 2 human toxicity cancer and non-cancer categories, with characterization factors equal to zero for the emission context considered. In contrast, toluene losses to air lead to non-zero human toxicity non-cancer impacts (9.29×10^{-6} cases), indicating that chronic exposure

Table 5 Summary of upstream contributions to GWP-100 of the Swenson process of sugarcane raw wax production using heptane and toluene in Brazil and Cuba. Some upstream processes are not shown (or appear as 0.00) because the background dataset is modelled under the recycled-content cut-off approach (ecoinvent “Cutoff, U-...”). In such cases, 0.00 indicates “cut-off/zero contribution in the selected dataset,” not a missing inventory item

Process	Required amount	Unit	Total result (kg CO ₂ eq/t raw wax)		Contribution (%)	
			Brazil	Cuba	Brazil	Cuba
HEPTANE						
Market for electricity, low voltage electricity, low voltage Cutoff, U - BR-North-eastern grid or CU	24,935	MJ	2772	7389	59.2	79.4
Steam production, in chemical industry steam, in chemical industry Cutoff, U - RoW	4238	kg	1401	1405	29.9	15.1
Market for heptane heptane Cutoff, U - GLO	800.87	kg	507	509	10.8	5.5
Rainwater harvesting water, harvested from rainwater Cutoff, U - GLO	27,740	kg	7	7	0.1	0.1
Raw Wax Production - heptane - BR-BA or CU	1000.00	kg	4686	9310	100.0	100.0
TOLUENE						
Market for electricity, low voltage electricity, low voltage Cutoff, U - BR-North-eastern grid or CU	27,927	MJ	3103	8239	47.7	70.9
Market for toluene, liquid toluene, liquid Cutoff, U - RER	1139	kg	1774	1801	27.3	15.5
Steam production, in chemical industry steam, in chemical industry Cutoff, U - RoW	4747	kg	1568	1568	24.1	13.5
Market for filter cake, from sugarcane juice filtration filter cake, from sugarcane juice filtration Cutoff, U-GLO	72,727	kg	48	0.00*	0.7	0.0*
Rainwater harvesting water, harvested from rainwater Cutoff, U - GLO	31,069	kg	7	7	0.1	0.1
Raw Wax Production - toluene - BR-BA or CU	1000.00	kg	6501	11,616	100.0	100.0

* 0.00 indicates a cut-off/zero upstream burden for the “market for filter cake ... Cutoff, U-GLO” background dataset under the recycled-content cut-off system model

Table 6 GWP-100 impact ranges (95% confidence interval) for raw cane wax production using different solvents in Brazil and Cuba based on Monte Carlo simulation results

Route	Country	Lower limit (kg CO ₂ eq./t raw wax)	Upper limit (kg CO ₂ eq./t raw wax)
Route 1	Brazil	3548	6244
- heptane	Cuba	6754	12,420
Route 2	Brazil	4385	7909
- toluene	Cuba	7519	14,401

concerns are meaningfully higher for toluene than for heptane, even though the absolute magnitude remains low.

Although the characterization factor and the impact assessment are significantly low, and the World Health Organization (WHO) and other international organizations have estimated non-hazardous levels of toluene in the atmosphere, it is known that constant exposure to this toxic substance results in chronic toxicity with negative effects on human health [43–46].

Global warming potential analysis

The Global Warming Potential over a 100-year timescale (GWP-100) analysis revealed distinct impacts for both process routes across the two countries. For the heptane route, the baseline GWP100 is 4.9×10^3 kg CO₂ eq per tonne of raw wax in Brazil and 9.6×10^3 kg CO₂ eq per tonne in Cuba, whereas for toluene the corresponding values are 6.1×10^3 and 11.0×10^3 kg CO₂ eq per tonne, respectively (Table 5). In both countries, the toluene route exhibits higher GWP100 than the heptane route, with relative increases of approximately 25% in Brazil and 15% in Cuba. The contribution analysis shows that low-voltage electricity is the dominant driver of climate change impacts, accounting for 59–79% of total GWP100 depending on route and country, followed by steam production (13 to 30%) and solvent production (5 to 27%). Detailed representations of the impact chains are provided in Appendix D.

Uncertainty analysis results

However, it is necessary to reconsider the uncertainties of these results, being influenced by the variety of cane, climate, cane harvest, juice extraction, and other factors, aggregated into a total impact unit. These uncertainties were estimated through Monte Carlo simulations with 5,000 iterations, and were used to quantify the combined effect of inventory uncertainty on GWP100. The resulting 95% coverage intervals are summarized in Table 6. For the heptane route, GWP100 ranged from 3,548 to 6,244 kg CO₂ eq per tonne in Brazil and from 6,754 to 12,420 kg CO₂ eq per tonne in Cuba, while for the toluene route the corresponding

ranges were 4,385 to 7,909 kg CO₂ eq per tonne and 7,519 to 14,401 kg CO₂ eq per tonne, respectively. The relative standard uncertainties were of the order of 27 to 31% for all scenarios. Despite these uncertainties, the ranking of scenarios was robust: in all cases, the heptane route in Brazil exhibited the lowest GWP100, followed by toluene in Brazil, heptane in Cuba, and toluene in Cuba.

Discussion

The LCA of the Swenson process for raw cane wax extraction reveals several critical insights regarding both process optimization and geographical implementation considerations. The following discussion focuses on three key aspects: solvent selection, geographical implications, and opportunities for enhancing process sustainability.

Solvent selection and environmental impact

The comparative analysis between heptane and toluene as extraction solvents demonstrates clear environmental advantages for the currently employed heptane-based process. Based on the deterministic baseline results (Table 5), the GWP-100 impact assessment shows that the heptane process generates significantly lower emissions (9,310 kg CO₂ eq/t raw wax in Cuba and 4,686 kg CO₂ eq/t raw wax in Brazil) compared to the toluene route (11,616 and 6,501 kg CO₂ eq/t raw wax, respectively). As presented in Appendix C and Table 6, the Monte Carlo simulations confirm the robustness of this scenario ranking under uncertainty, yielding stochastic means of $(9.6 \pm 2.8) \times 10^3$ and $(4.9 \pm 1.3) \times 10^3$ kg CO₂ eq/t for heptane in Cuba and Brazil, respectively, compared to toluene's $(11.0 \pm 3.4) \times 10^3$ and $(6.1 \pm 1.8) \times 10^3$ kg CO₂ eq/t. This difference becomes more pronounced when considering the USEtox[®] 2 toxicity impact analysis, where heptane showed negligible toxicity impacts, while toluene exhibited measurable human non-cancer toxicity effects (9.29×10^{-6} cases/kg). Although this toxicity level is relatively low, the chronic exposure risks associated with toluene emissions make it a less favorable option for large-scale industrial implementation.

Solvent–wax affinity quantified by HSP parameters (R_a , RED, and R_0) directly influences extraction efficiency, which in turn determines solvent circulation intensity, heating requirements, and the steam and electricity load of the Swenson process. Higher affinity (lower R_a/R_0 ratios) improves extraction, reducing the thermal duty for solvent evaporation and lowering overall energy demand. Because energy consumption (particularly steam production and electricity use) is the dominant contributor to GWP100 across both regions, molecular-scale interactions propagate

into macro-level environmental outcomes. This mechanistic linkage strengthens the methodological integration between HSP screening and LCA interpretation.

The solvent selection criteria developed through HSP analysis identified several potential alternatives, including o-xylene and cyclohexane. O-xylene has a high boiling point and vacuum distillation should be implemented in the existing plant for its recovery. Additionally, due to a lack of available industrial extraction yield data for these specific compounds, a full environmental comparison was not possible. Therefore, further experimental validation of these alternatives is necessary to overcome this data-availability constraint before considering them as viable replacements for heptane. The ideal solvent must achieve superior environmental performance per unit of wax yield, while also providing adequate extraction efficiency and ensuring compatibility with Swenson's existing process infrastructure.

Geographical implementation considerations

The comparative assessment between Cuban and Brazilian implementations reveals substantial differences in environmental impact, primarily driven by variations in the electricity mix between the two countries. The notably lower GWP-100 values for Brazil (approximately 48% lower than Cuba for both solvent options) suggest that implementing this technology in Brazil could offer significant environmental advantages. This finding is particularly relevant given Brazil's position as the world's leading sugarcane producer, accounting for 38% of global production in 2022.

Transportation was set to zero for both regions under a *ceteris paribus* assumption. In Cuba, this reflects the actual operational layout of the Majibacoa facility, where the Swenson extraction unit, evaporator, separator, and purification system are co-located within approximately 20 m, with no external vehicle-based transportation.

For Brazil, no industrial plant implementing the Swenson process exists to date; therefore, no empirical information is available regarding internal distances, equipment layout, or transportation modality. Because the purpose of the regional comparison was to isolate the influence of the electricity matrix, all other parameters (including transportation) were conservatively held constant.

As transportation impacts in Brazil will ultimately depend on the specific design of a future facility, we outline in this section a methodological framework for estimating a 'reversal distance' (d_{rev}) for which Brazilian impacts ($Mass_{transport}$) may exceed Cuban impacts (GWP). To evaluate the robustness of the Brazilian scenario against potential logistical burdens, a break-even analysis was performed, based on this algorithm:

$$\Delta GWP = d_{rev} \times Mass_{transport} \times \text{Emission Factor}.$$

The baseline GWP-100 advantage of the heptane route in Brazil compared to Cuba is approximately 4,700 kg CO₂ eq per tonne of wax. Assuming the transport of wet filter cake (approximately 65 tonnes per tonne of wax produced, based on process mass balances) using heavy-duty lorries with a standard Emission Factor of 0.16 kg CO₂ eq/t-km (Ecoinvent v3.6), the transport-related emissions would amount to roughly 10.4 kg CO₂ eq per kilometer of distance. Consequently, the 'reversal distance' - the transport radius at which the grid-related environmental benefits are fully negated by transport emissions - is estimated to be approximately 450 km. This suggests that for the environmental advantage to hold, a future Brazilian facility should be sited within this radius of the supplier sugar mills, a constraint that is logistically feasible within the dense sugarcane clusters of São Paulo or Bahia.

Future work and sustainability perspectives

The LCA results highlight three priority levers for reducing GWP100 in the Swenson process: (i) the electricity mix, which dominates upstream contributions to climate change; (ii) steam demand for solvent recovery, which is the second largest contributor; and (iii) solvent selection, given the higher impacts and toxicity associated with toluene compared with heptane. Beyond the system boundaries considered in this study, additional circular-economy strategies could be explored in future work, such as anaerobic digestion of exhausted filter cake to produce biogas and the use of digested residues as biofertilizer in sugarcane cultivation. These options were not modelled in the present LCA and are therefore discussed only as prospective pathways.

Process optimization presents another avenue for environmental impact reduction. While the current process achieves high solvent recovery rates, further optimization of recovery systems could reduce both environmental impact and operational costs. The implementation of heat integration strategies could address steam consumption, which currently contributes 15 to 30% of total GWP-100 impact, representing a significant opportunity for improvement.

Future research directions should focus on several key areas for advancement. The development of hybrid solvent systems could potentially combine the environmental advantages of heptane with enhanced extraction efficiency. Investigation of process intensification strategies may reveal opportunities to reduce energy consumption while maintaining product quality. Additionally, the exploration of alternative filter cake pre-treatment methods could enhance extraction efficiency and reduce solvent requirements.

These findings have significant implications for the sugarcane industry's transition toward more sustainable practices. The demonstrated viability of the Swenson process,

particularly in the Brazilian context, suggests that widespread implementation could contribute substantially to the valorization of sugarcane processing residues while supporting circular economy principles. However, successful implementation will require careful consideration of local conditions and continued optimization of process parameters to maximize environmental benefits.

The relative standard uncertainties in our GWP-100 results (ranging from 27% to 31%) indicate that additional experimental work and field data collection would be valuable for reducing these uncertainties and further refining our understanding of the process's environmental impact. This uncertainty analysis strengthens the case for continued research and optimization of the Swenson process while highlighting the robustness of our primary conclusions regarding solvent selection and geographical implementation considerations.

Conclusions

The life cycle assessment of the Swenson process for raw cane wax extraction demonstrates that the heptane-based process generates lower environmental impacts compared to potential toluene-based alternatives. The total GWP-100 impact using heptane was estimated at $(9.6 \pm 2.8) \times 10^3$ kg CO₂ eq/t raw wax for operations in Cuba and $(4.9 \pm 1.3) \times 10^3$ kg CO₂ eq/t raw wax for Brazil. The toluene-based alternative showed higher impacts of $(11.0 \pm 3.4) \times 10^3$ and $(6.1 \pm 1.8) \times 10^3$ kg CO₂ eq/t raw wax for Cuba and Brazil, respectively, while also presenting measurable toxicity risks that were absent in the heptane-based process.

The geographical comparison revealed that implementation in Brazil could reduce environmental impacts by approximately 48% compared to Cuba, primarily due to differences in electricity grid composition. This finding, combined with Brazil's significant sugarcane production capacity, suggests potential benefits for technology implementation in this region, though transportation logistics require careful consideration. The sensitivity analysis showed that the GWP-100 advantage of the Brazilian heptane-based scenario is preserved even when accounting for transport-related emissions from wet filter cake, provided that the future facility is located within approximately 450 km of the supplying sugar mills.

Several opportunities exist for enhancing process sustainability, including improved water recovery systems, biogas generation from filter mud, and utilization of exhausted filter cake as organic fertilizer. The relative standard uncertainties in the results (27 to 31%) indicate that additional experimental data could further refine these findings.

Future research directions should focus on identifying alternative green solvents, optimizing heat integration strategies, and investigating process intensification opportunities. The demonstrated viability of the Swenson process, particularly in the Brazilian context, indicates its potential role in the sustainable development of sugarcane biorefineries.

Supporting information

Supporting information containing methodological supplements and uncertainty assessment tools, Monte Carlo simulations, and Sankey Diagrams will be available in the Zenodo open-access repository, maintained by the European OpenAIRE Program and operated by the European Organization for Nuclear Research (CERN).

The supporting materials are organized in two supplements:

- Supplement 1 - Methods and Instruments for Assessing Uncertainties (Appendices A and B).
- Supplement 2 - Monte Carlo simulations and Sankey Diagrams: Swenson process of sugarcane raw wax production (Appendices C and D).

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