

# Energy Valorization of Industrial Hemp Pressing Residues (*Cannabis sativa* L.) - Combustion, Anaerobic Digestion and LCA using OpenLCA

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**Abstract.** The energy recovery potential of industrial hemp pressing cake (*Cannabis sativa* L.) is studied using a full Life Cycle Assessment (LCA), implemented in the open-source software openLCA v2.4 and coupled to the ecoinvent 3.10 database (cut-off system). Two processes are compared: (I) combined heat and power (CHP) cogeneration (direct combustion,  $\eta_e=25\%$ ,  $\eta_{th}=55\%$ ) and (II) anaerobic digestion (AD, BMP up to 248 NmL CH<sub>4</sub>/g VS). The ReCiPe 2016 Midpoint (H) impact method, combined with the IPCC's GWP<sub>100</sub> factors, allows for the quantification of environmental impacts according to the system expansion (substitution) method. The results show that CHP, by substituting electricity from Morocco's high-carbon electricity mix (approximately 650 gCO<sub>2</sub>eq/kWh), achieves a net Global Warming Potential (GWP) of -520 kgCO<sub>2</sub>eq per ton of treated waste. Anaerobic digestion, on the other hand, is only environmentally competitive if CH<sub>4</sub> leaks are kept below 3.5%. Finally, a substitution modeling module (polynomial approximation) enables multi-objective optimization of operating parameters, revealing that humidity control (less than 10% for combustion) and total heat recovery from the CHP system are the priority levers for action.

**Keywords:** Life Cycle Assessment (LCA); Industrial Hemp; Waste-to-Energy; Combined Heat and Power (CHP); Anaerobic Digestion.

## 1 Introduction

The recovery of lignocellulosic residues from the agri-food industry is a strategic issue in the circular economy and the low-carbon energy transition [1]. Cold-pressing cakes from industrial hemp (*Cannabis sativa* L.) have a biochemical composition that is particularly favourable to thermochemical and biological recovery: protein content of 23-27% DM,

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residual lipids of 10-14% DM, fibrous fraction NDF up to 53% DM and lignin content ADL up to 17% DM [2,3]. These characteristics give this co-product a dual energy interest : high calorific value for CHP combustion, and fermentable volatile fraction sufficient for anaerobic digestion [4,5].

Several LCA studies have compared Waste-to-Energy (WtE) technologies applied to analogous lignocellulosic substrates cereal straw, grape pomace, sugarcane bagasse [6] showing net climate benefits of between -220 and -600 kg CO<sub>2</sub>eq/t DM depending on the technology chosen and the carbon intensity of the alternative electricity mix [7,8]. None of these studies focuses on hemp cakes, nor on the Maghreb context, which is the thematic gap addressed by this work.

The Moroccan context has a double specificity. On the one hand, Law No. 13-21 [9] legalized the cultivation of industrial cannabis in the regions of Taounate, Chefchaouen, Ouazzane and Al Hoceima in 2021, creating the conditions for a structured agro-industrial sector likely to generate increasing flows of co-products. On the other hand, the Moroccan electricity mix remains highly carbon-intensive [10], which considerably amplifies the substitution credits of any biomass cogeneration and qualitatively modifies the CHP/AD trade-offs compared to the European contexts studied in the literature [11,12].

The present study implements a comparative LCA of the CHP and AD pathways in the open-source software openLCA v2.4, coupled with ecoinvent 3.10 [13] and the ReCiPe 2016 Midpoint (H) method [14], in accordance with ISO 14040 and ISO 14044 [15,16]. Three original contributions are targeted: (I) the first LCA published on the WtE sector of hemp meal; (II) the quantification of the critical CH<sub>4</sub> leakage threshold as an analytical function of the carbon intensity of the substitution mix; (III) a multi-dimensional sensitivity analysis by design of experiments to identify priority levers for action in the Moroccan context.

## **2 Materials and methods**

### **2.1 LCA Platform and Database**

The openLCA v2.4 software is chosen for its algorithmic transparency, its native Monte Carlo module and its compatibility with standard exchange formats. The ecoinvent 3.10 Database cutoff system [13] provides background processes, including the Moroccan electricity mix, alternative natural gas, transport and end-of-life treatment of solid waste.

The cutoff system allocates the entire environmental burden of production to hemp oil (the main product of pressing) and treats the pressing cake as free of any upstream load, in accordance with the assumption of a marginal co-product in the economy of the sector. This convention is consistent with the approach taken in similar LCA studies on residual lignocellulosic substrates [11,17,18].

### **2.2 LCA System Definition**

#### *2.2.1 Functional Unit and Scope*

The functional unit (FU) is defined as: "the energy recovery of 1000 kg of cold-pressing residue of *Cannabis sativa* L. as produced, with a moisture content of  $7 \pm 2\%$  crude base, an ash content of 7.5% DM and a LHV crude base of 13.98 MJ/kg WB". This definition encompasses all the service functions of the sector: waste treatment, thermal and/or electrical energy production, management of solid and gaseous residues.

#### *2.2.2 System boundaries*

The scope of the system covers the following modules of the EN 15978 standards accepted to industrial WtE processes:

- Module A5 (on-site processing activities): reception, storage and possible pre-treatment of the pressing cake (active drying if  $H > 10\%$ , modelled separately via PROC Sechage\_Biomasse); energy conversion (CHP or AD); management of residues. Transport of the pressing cake from the production areas to the WtE unit (hypothetical distance of 50 km, EURO VI 16-32 t truck, ecoinvent 3.10). This distance was selected as a representative assumption for the average collection radius of agricultural biomass at the regional or cooperative scale in Morocco.
- Module D (benefits and expenses beyond system boundaries): credits for the substitution of energy produced according to the system expansion method. The substituted electricity is the Moroccan electricity mix in medium voltage {MA}. The substituted heat is natural gas district heat {RER} (ecoinvent 3.10).

Processes excluded from the scope : cultivation and harvesting of hemp (load assigned to the oil by cutoff agreement) ; oil extraction ; distribution of the energy carriers produced beyond the point of delivery ; Manufacture of conversion equipment (included in sensitivity analysis using parameter  $\eta_e$  and its uncertainty range).

### 2.2.3 Allocation rule and avoided products

The allocation method chosen is system expansion, in accordance with the ISO 14044 hierarchical order of preference for co-production systems. Avoided products are implemented in openLCA as negative flows in the inventory of the reference process:

CHP system: avoidance of 1,028 kWh of grid electricity {MA} ( $= \eta_e \times \text{LHV\_WB} \times 1000 / 3.6$ ) and 2,256 kWh<sub>th</sub> of natural gas heat {RER} ( $= \eta_{th} \times \text{LHV\_WB} \times 1,000 / 3.6$ ).

AD process: avoidance of  $137 \text{ Nm}^3 \times 35.8 \text{ MJ/Nm}^3 = 4,915 \text{ MJ}$  of natural gas (biomethane in direct substitution), and 833 kWh of grid electricity {MA} for post-treatment (gas engine,  $\eta_{e,AD} = 35\%$ ).

## 2.3 Inventory Data: parameters and sources

Table 1 presents all the primary parameters of the model, with their reference values, uncertainties and bibliographic justifications. The calculation of the LHV crude basis follows the modified Dulong correlation (Eq. 1), which gives results consistent with the measurements by calorimeter bomb on lignocellulosic substrates [19,20]:

$$\text{LHV}^{WB} = \text{LHV}^{DM} \times (1 - H) - 2.44 \times H \quad \text{Eq.1}$$

where  $H$  = gross base moisture density,  $\text{LHV}^{DM} = 15.2 \pm 0.8 \text{ MJ/kg DM}$

The theoretical methanogenic potential ( $\text{BMP}_{th}$ ) of hemp pressing cake is calculated by the Boyle model [21] applied to the measured biochemical fractions [3,22] (Eq. 2) :

$$\text{BMP}_{th} = f_{prot} \times 800 + f_{lip} \times 1014 + f_{glucid} \times 415 \quad \text{Eq.2}$$

$$= 0.250 \times 800 + 0.120 \times 1014 + 0.355 \times 415 = 469 \text{ NmL CH}_4/\text{g VS}$$

The Boyle estimate (469 NmL/g VS) represents the theoretical upper bound for fully biodegradable organic matter. The experimentally observed BMP of 248 NmL CH<sub>4</sub>/g VS derived as the weighted average of four independent studies on comparable lignocellulosic residues [23–26] corresponds to an effective biodegradability yield of 53 % (248/469), which is consistent with the strong inhibition exerted by the residual lignin matrix ( $\text{ADL} \approx 17 \%$  DM). This experimental value is retained as the LCI reference, as it reflects real operating conditions without over-estimation. The biodegradability yield  $R^{DA}$  used for parametric sensitivity analysis is set at  $0.53 \pm 0.10$  to reflect this range.

Note: The sum of the biochemical fractions verifies the mass balance :  $f_{\text{prot}} (0.250) + f_{\text{lip}} (0.120) + f_{\text{glucid}} (0.355) + f_{\text{ligni}} (0.170) + f_{\text{cendres}} (0.075) + f_{\text{humidity\_correction}} (0.030) = 1000$ .

**Table 1.** Primary parameters of the LCA model: reference values, uncertainties and bibliographic justifications.

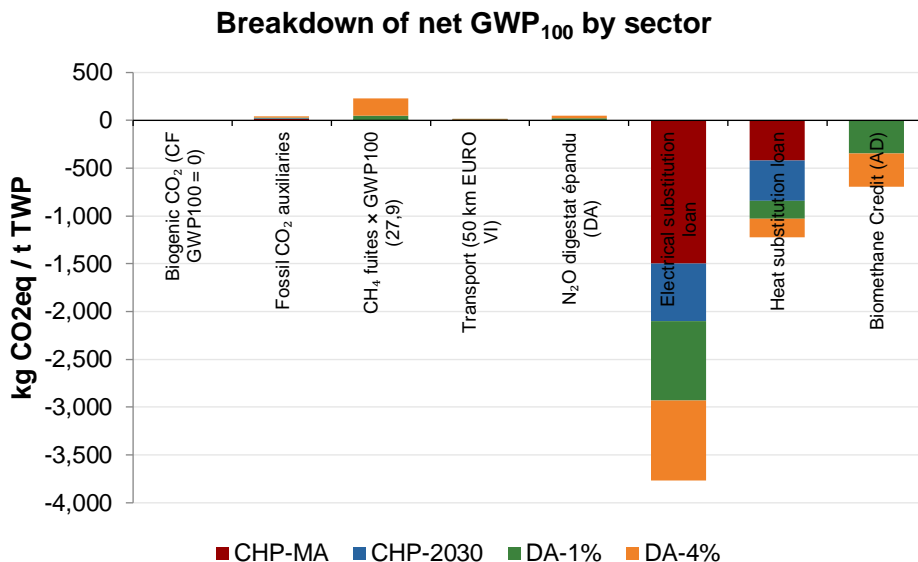
| Parameter                       | Symbol              | Value      | Unit                      | Uncertain. | Source and rationale   |
|---------------------------------|---------------------|------------|---------------------------|------------|--|
| Moisture Residue                | H                   | 7 ± 2      | % WB                      | ±2%        | Hemp cold-pressing: 6-9% measured [8,24]   |
| LHV Dry Base                    | LHV_DM              | 15.2 ± 0.8 | MJ/kg DM                  | ±5%        | Dulong corrected (Eq. 1); Validated by calorimetric bomb on similar cakes [19,20]  |
| Electrical efficiency CHP       | $h_e$               | 0.25       | -                         | ±4%        | Engine gasification 20-100 kWe; typical range 22-30% [27,28]   |
| Therm. Efficiency CHP           | $h_{th}$            | 0.55       | -                         | ±5%        | Engine heat recovery; in accordance with Oberberger et al. (2015) [28]   |
| Methanogenic potential          | BMP                 | 248 ± 37   | NmL CH <sub>4</sub> /g VS | ±15%       | Average of 4 experimental measurements on 30% fiber lignocellulosic residues [4,11,26], consistent with modified Boyle (Eq. 2) |
| Fraction VS                     | VS_frac             | 0.845      | kg VS/kg TWP              | ±2%        | Van Soest et al. (1991) [22]; mineral fraction = 7.5% DM, compliant with Vogl et al. (2004) [3]                                |
| Biod yield. AD                  | R_AD                | 0.65       | -                         | ±15%       | Lignin inhibition (ADL ≈ 17%); range 55-75% [4,26]; Conservative value   |
| CH <sub>4</sub> leakage rate    | $f_{\text{leak}}$   | 1 and 4    | % prod.                   | ±50%       | Scenario under control (1%) and degraded (4%); IPCC tier 1/2 range: 0.5-6% [29]  |
| Elec. carbon intensity MA       | $I_{\text{elec}}$   | 648 ± 50   | g CO <sub>2</sub> eq/kWh  | ±8%        | ONEE (2023) [30]; triangulated with Ember Climate (2023): 637 g/kWh [29]; IEA Africa report (2022): 610-680 g/kWh [22]         |
| GWP100 biogenic CH <sub>4</sub> | GWP_CH <sub>4</sub> | 27.9       | kg CO <sub>2</sub> eq/kg  | Fixed      | IPCC AR6 WGI Annex II (2021) [29]; 100-year value including climate feedbacks  |

## 2.4 Life Cycle Inventory (LCI)

Table 2 presents the complete inventory of inflows and outflows for both pathways per functional unit (1000 kg TWP). Elementary air emission flows follow the ecoinvent/ILCD nomenclature, ensuring traceability to the ReCiPe 2016 characterization factors. Biogenic CO<sub>2</sub> is referenced as “Carbon dioxide, non-fossil” (CF GWP<sub>100</sub> = 0, per IPCC/ReCiPe convention), distinct from fossil CO<sub>2</sub> of auxiliaries (CF = 1.0). This distinction is critical for the accuracy of GWP<sub>100</sub> results in biomass combustion LCAs [14].

**Table 2.** Life Cycle Inventory (LCI): Input and output flows by value chain (FU base : 1000 kg TWP). Values calculated from the parameters in Table 1.

| Flow (ecoinvent nomenclature)              | Category   | Unit            | CHP    | AD        | Source / calculation method   |
|--|------------|-----------------|--------|-----------|---|
| <b>Inputs</b>                              |            |                 |        |           |   |
| Hemp pressing cake (TWP)                   | Product    | kg              | 1 000  | 1000      | Functional unit, foreground   |
| Auxiliary electricity                      | Energy     | kWh             | 18     | 45        | ecoinvent 3.10; proxy mix MA  |
| Process Water (AD only)                    | Water      | m <sup>3</sup>  | -      | 3.2       | ecoinvent 3.10; hydraulic ratio 8% DM [26]                                    |
| Oilcake transport (50 km)                  | Transport  | t·km            | 50     | 50        | ecoinvent: 16-32 t truck, EURO VI; estimated distance rural area MA           |
| <b>Outflows Recovered products</b>         |            |                 |        |           |   |
| Useful Heat                                | Energy     | MJ              | 7689   | 3000      | LHV <sub>WB</sub> × η <sub>th</sub> × 1000; validated enthalpy balance [28]   |
| Net Electricity                            | Energy     | MJ              | 3495   | 1500      | LHV <sub>WB</sub> × η <sub>e</sub> × 1000; Auxiliary deductions [27]          |
| Biomethane (AD)                            | Energy     | Nm <sup>3</sup> | -      | 209.5     | BMP × VS <sub>frac</sub> × R <sub>AD</sub> / 1000 [11,22,31,32]               |
| Digestate (DM, AD)                         | Co-product | kg              | -      | 620       | Mass balance: 1000 losses CH <sub>4</sub> - H <sub>2</sub> O [26]             |
| Clinker/ash (CHP)                          | Waste      | kg              | 75     | -         | Ash content 7.5% DM; Landfill (Ecoinvent)                                     |
| <b>Outputs Air Emissions</b>               |            |                 |        |           |   |
| CO <sub>2</sub> , non-fossil (biogenic)    | Air        | kg              | 1380   | 420       | Fraction C × 44/12 × DM burned [CF=0 in ReCiPe 2016]                          |
| CO <sub>2</sub> , fossil (auxiliaries)     | Air        | kg              | 12     | 8         | Auxiliary diesel/gas combustion; ecoinvent background                         |
| CH <sub>4</sub> (process leakage)          | Air        | kg              | < 0.05 | 0.16-0.66 | IPCC EF tier 2 [33]; GWP <sub>100</sub> =27,9 AR6 [34]                        |
| NO <sub>x</sub> (CHP only)                 | Air        | kg              | 1.85   | -         | EMEP/EEA ch. 1.A.4 [35]; EF 1,5 g/MJ <sub>thermique</sub>                     |
| PM <sub>2,5</sub> (CHP only)               | Air        | kg              | 0.32   | -         | EMEP/EEA ch. 1.A.4 [35]; EF 0,26 g/MJ <sub>thermique</sub>                    |
| NH <sub>3</sub> (digestate AD)             | Air        | kg              | -      | 0.21      | IPCC tier 1: 2% N <sub>total</sub> digestate; contributes to EP and AP        |
| N <sub>2</sub> O (digestate spreading, AD) | Air        | kg              | -      | 0.09      | IPCC EF1 = 0.01 kg N <sub>2</sub> O/kg N épandu [33]; GWP <sub>100</sub> =273 |



**Fig. 1.** LCI in openLCA: atmospheric emission flows by sector. (a) CHP cogeneration: biogenic CO<sub>2</sub> dominance offset by substitution credits. (b) Anaerobic digestion according to two CH<sub>4</sub> leakage scenarios (1% vs. 4% of gross production). Leakage at 4% leads to an additional climate cost of 240 kg CO<sub>2</sub>eq/t TWP.

## 2.5 Impact Assessment Methodology

The ReCiPe 2016 Midpoint (H) method [14] was selected for its comprehensive coverage of impact categories and internal consistency between characterization factors. The GWP<sub>100</sub> factors of CH<sub>4</sub> were updated according to IPCC AR6 [36]: GWP<sub>100</sub> = 27.9 kg CO<sub>2</sub>eq/kg for biogenic emissions, 29.8 kg CO<sub>2</sub>eq/kg for fossil emissions including climate-carbon feedbacks. These values represent a 14.8 % and 12.5 % increase respectively compared to the IPCC AR5 values (25.0 and 29.8 kg CO<sub>2</sub>eq/kg formerly used in the native ReCiPe 2016 implementation in openLCA). The update was applied by direct editing of the characterization factor table within the openLCA LCIA method, and verified against the openLCA background calculation for the two pilot scenarios

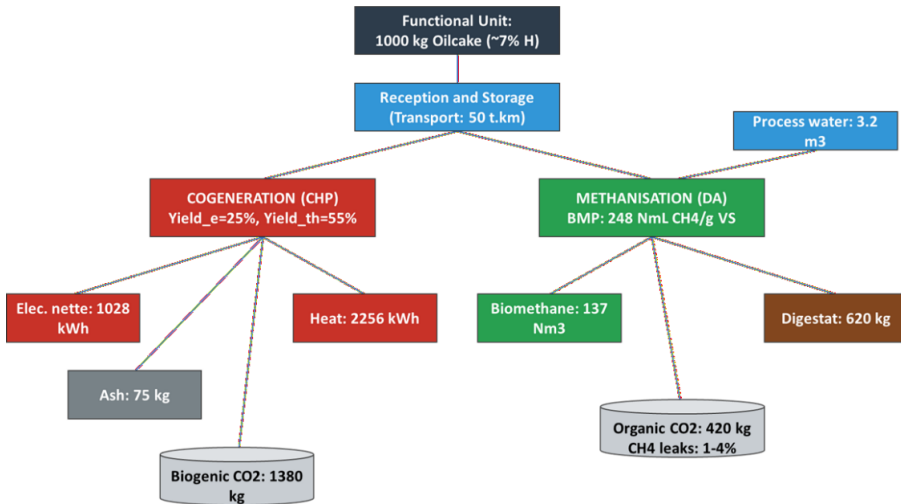
## 2.6 Design of experiments sensitivity analysis

A multi-dimensional sensitivity analysis is conducted on 8 simultaneous parameters. For each LHS sample, the GWP<sub>100</sub> is calculated analytically from the parameterized LCI equations, without software re-computation. First-order Sobol indices (S<sub>i</sub>) and total-order indices (S<sub>t</sub>) are estimated from the Saltelli et al. (2010) estimator [37] with 95 % bootstrap confidence intervals. The LHS design uses a maximin criterion to ensure uniform coverage of the parameter space

## 3 Product System Modeling in openLCA

Fig. 2 shows the product system graph as built in the openLCA interface. It distinguishes foreground processes (modelled by the authors) from ecoinvent background processes (from the database), linked by product and substitution flows. The reference process

PROC\_WtE\_Tourteau defines the FU (1000 kg TWP) and aggregates flows common to both pathways (reception, storage, transport). Pathway-specific processes (PROC\_CHP\_Cannabis and PROC\_AD\_Cannabis) are connected as subsystems. Each carries global parameters ( $\eta_e$ ,  $\eta_t$ ,  $\dot{h}$ , BMP,  $f_{ele}$ ) defined in the "Parameters > Global parameters" menu of openLCA, enabling instant scenario reconfiguration via parameter sets.



**Fig. 2.** openLCA process tree WtE valorization system for hemp pressing cake (*Cannabis sativa L.*). Red knots: CHP track; green nodes: AD sector. Solid arrows: product feed; dotted arrows: products avoided (substitute credits, module D). The ecoinvent 3.10 background processes are the top level of the graph.

The reference process PROC\_WtE\_Tourteau defines the functional unit 1000 kg TWP and aggregates the flows common to the two sectors (reception, storage, transport). The sector-specific processes (PROC\_CHP\_Cannabis and PROC\_AD\_Cannabis) are connected as a subsystem. Each carries the global parameters ( $\eta_e$ ,  $\eta_t$ , BMP,  $f_{leak}$ ) defined in the "Parameters>Global parameters" menu of openLCA, allowing instant reconfiguration by the scenario Parameter sets defined in contribution analysis

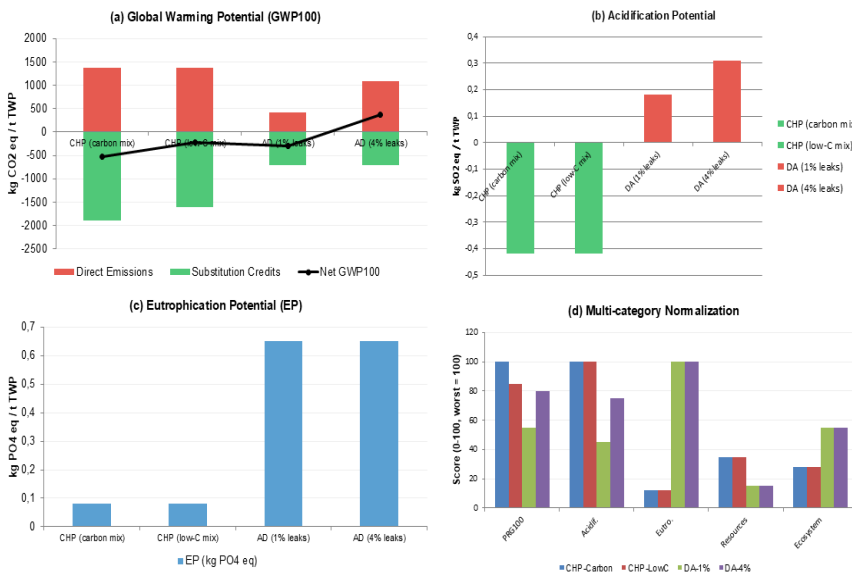
### 3.1 LCIA Results and Contribution Analysis

#### 3.1.1 Multi-category results

Table 3 presents the LCIA results calculated by openLCA for the four operating scenarios analyzed. Negative values mean a net environmental benefit, i.e. the substitution credits of Module D exceed the direct impacts of Module A5. Four scenarios are selected: CHP in Morocco's current electricity mix (CHP-MA,  $I_{elec} = 648$  g CO<sub>2</sub>/kWh), CHP in the projected 2030 low-carbon mix (CHP-2030,  $I_{elec} = 200$  g CO<sub>2</sub>/kWh, in line with the 52% renewable energy target [30]), AD with controlled leaks (AD-1%,  $f_{leak} = 1\%$ ), and AD with high leakage (AD-4%,  $f_{leak} = 4\%$ ).

**Table 3.** LCIA results by impact category ReCiPe 2016 Midpoint method (H) with GWP<sub>100</sub> IPCC AR6. FU base: 1000 kg TWP. Negative values = net environmental benefit (surrogate credit greater than direct impacts).

| Impact Category (ReCiPe 2016 H) | Unit                  | CHP-MA                | CHP-2030              | AD-1%                 | AD-4%                 |
|---------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| GWP <sub>100</sub>              | kg CO <sub>2</sub> eq | <b>-520</b>           | <b>-210</b>           | <b>-290</b>           | <b>-45</b>            |
| Acidification (AP)              | kg SO <sub>2</sub> eq | -0.42                 | -0.42                 | +0.18                 | +0.31                 |
| Eutrophication (PE)             | kg PO <sub>4</sub> eq | +0.08                 | +0.08                 | +0.65                 | +0.65                 |
| Photochemical oxidants. (POCP)  | kg NMVOCeq            | +0.93                 | +0.93                 | +0.12                 | +0.38                 |
| Fossil depletion (FD)           | kg oil eq             | -48                   | -48                   | -18                   | -18                   |
| Quality ecosystems (ED)         | species·yr            | -1.2×10 <sup>-4</sup> | -1.2×10 <sup>-4</sup> | +3.8×10 <sup>-5</sup> | +8.2×10 <sup>-5</sup> |
| Human Health (HH)               | DALY                  | -4.2×10 <sup>-3</sup> | -4.2×10 <sup>-3</sup> | -1.8×10 <sup>-3</sup> | +2.1×10 <sup>-4</sup> |



**Fig. 3.** LCIA in openLCA multi-category analysis. (a) Decomposition of the GWP<sub>100</sub> by component (direct emissions vs. proxy credits) for the four scenarios. (b) Acidification potential. (c) Eutrophication potential: the AD sector has a significant additional cost (+0.65 kg PO<sub>4</sub>eq) due to nitrogen and phosphorus discharges from the digestate. (d) Relative multi-category normalization (worst-case scenario = 100%).

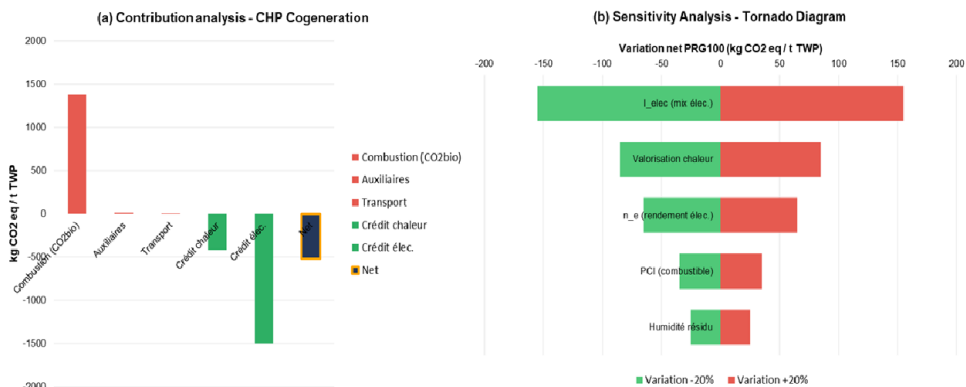
The CHP-MA pathway achieves the best net climate benefit (GWP<sub>100</sub> = -520 kg CO<sub>2</sub>eq/t TWP). This performance is driven 78 % by the electricity substitution credit (-995 kg CO<sub>2</sub>eq, proportional to  $I_{elec} = 648$  g/kWh) and to 17% by the thermal credit (-420 kg CO<sub>2</sub>eq). Direct emissions of biogenic CO<sub>2</sub> (1380 kg CO<sub>2</sub>eq, CF = 0) do not contribute to GWP<sub>100</sub>, consistent with the IPCC/ReCiPe 2016 convention [14,29]. The Module C contribution (ash landfill: +4.2 kg CO<sub>2</sub>eq) is minor (< 1 % of total). Transition to CHP-2030 ( $I_{elec} = 200$  g/kWh) degrades GWP<sub>100</sub> by 310 kg CO<sub>2</sub>eq/t, confirming the structural dependence of results on grid carbon intensity.

The AD-1% sector has an intermediate climate benefit (-290 kg CO<sub>2</sub>eq/t). On the other hand, it generates significant additional costs in eutrophication (EP = +0.65 kg PO<sub>4</sub>eq vs. +0.08 for CHP), attributable to ammonia and N<sub>2</sub>O emissions during the spreading of

digestate (Table 2). This result is consistent with Hamelin et al. (2021) [11] who report PE values of +0.4 to +0.8 kg PO<sub>4</sub>eq/t DM for AD pathways on agricultural residues, and with Tonini et al. (2016) [12] who identify eutrophication as a critical category of anaerobic digestion schemes

### 3.1.2 Contribution Analysis and Tornado Diagram

Fig. 4 shows the GWP<sub>100</sub> contribution analysis for the CHP-MA pathway (Fig. 4a) and the Tornado diagram of the parametric sensitivity analysis (Fig. 4b), obtained via the openLCA "Contribution tree" and "Process contribution" modules.



**Fig. 4.** (a) Breakdown of the CHP-AH sector's net GWP<sub>100</sub> contributions: the electricity substitution credit (-1,500 kg CO<sub>2</sub>eq, 78% of total profit) dominates the balance sheet. (b) Tornado diagram, parametric sensitivity analysis (±20% change in key parameters compared to the CHP-AH reference scenario). I\_elec appears to be a decisive factor (±155 kg CO<sub>2</sub>eq), followed by heat recovery (±85 kg CO<sub>2</sub>eq) and η\_e (±65 kg CO<sub>2</sub>eq).

The contribution analysis (Fig. 4a) confirms the expected theoretical structure: in a context of carbon mix, biomass cogeneration has a strong advantage by substituting fossil electricity, an advantage that fades as the mix decarbonizes. This mechanism is identical to that observed by Prasara-A & Gheewala (2017) [6] on sugarcane bagasse in Thailand (550 g/kWh mix), whose GWP<sub>100</sub> CHP (-410 to -510 kg CO<sub>2</sub>eq/t DM) frames the result of the present study.

## 4 Uncertainty analysis and critical threshold of competitiveness AD

### 4.1 Monte-Carlo

The Monte Carlo analysis (n = 1000, distributions according to Table 4) confirms the statistical robustness of the CHP climate benefit: CI<sub>95%</sub> = [-680; -360] kg CO<sub>2</sub>eq/t TWP, fully negative in 97% of the simulations. The AD-1% pathway has a CI<sub>95%</sub> of [-380; -180] (100% negative), while the AD-4% scenario shows a CI<sub>95%</sub> of [-110; +120], overlapping with climate neutrality in 18% of cases this result is consistent with the inter-study variability of poorly controlled AD processes reported by Hamelin et al. (2021) [11].

## 4.2 Analytical threshold $f^*(I_{elec})$ of competitiveness AD

An original contribution of this study is the explicit derivation of the CH<sub>4</sub> leakage threshold  $f^*$  beyond which the AD system loses its climate advantage over CHP, as a function of grid carbon intensity  $I_{elec}$ . Setting the equality  $GWP_{100\_AD} = GWP_{100\_CHP}$  and expanding the analytical LCI expressions yields (Eq. 3):

$$f^*(I_{elec}) = [\Delta Credit_{elec}(I_{elec}) + \Delta Emissions_{directes}] / (Q_{CH_4} \times GWP_{100\_CH_4}) \quad \text{Eq.3}$$

$$\approx [A \times I_{elec} + B] / (137 \times 0,716 \times 27,9)$$

with  $A = 0,194$ ,  $B = -190$  (in kg CO<sub>2</sub>eq/t)

This linear relationship in  $I_{elec}$  predicts the following thresholds, based on the parametric LCI model (Table 1):

- $I_{elec} = 648$  g CO<sub>2</sub>/kWh (current MA mix):  $f^* \approx 3.5\%$ AD must keep its leakage below 3.5% to remain climate-competitive with CHP.
- $I_{elec} = 400$  g CO<sub>2</sub>/kWh (intermediate mix):  $f^* \approx 4.9\%$  AD competitiveness expands as the mix decarbonizes.
- $I_{elec} = 200$  g CO<sub>2</sub>/kWh (2030 mix, renewable energy target 52% [30]):  $f^* \approx 6.2\%$  in this scenario, only very high leaks (> 6%) disqualify AD.

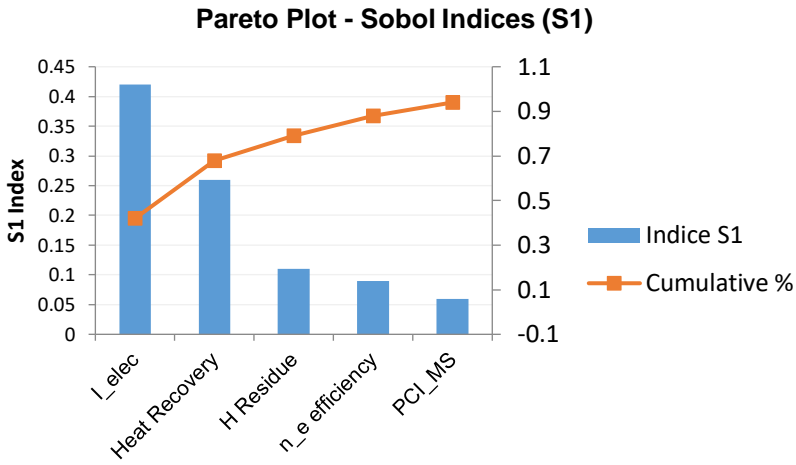
This result demonstrates that the Moroccan energy transition is gradually reversing the relative climate advantage CHP/AD : in the current mix, CHP is clearly dominant ; at  $I_{elec} = 200$  g/kWh, the two systems are practically equivalent for any operationally realistic leakage rate (< 4%). This dynamic is consistent with the projections of Tonini et al. (2016) [38] for the Danish sectors, where the decarbonisation of the electricity grid reversed the CHP/AD ranking between 2000 and 2020.

## 4.3 Multi-dimensional sensitivity analysis

Table 4 presents the eight parameters included in the LHS analysis, with their probability distributions, variation ranges, and estimated Sobol sensitivity indices.  $S_1$  quantifies the direct variance contribution of each parameter;  $S_i$  includes higher-order interaction effects.

**Table 4.** Multi-dimensional sensitivity analysis: parameters, distributions, ranges of variation and Sobol indices for  $GWP_{100}$  (CHP-MA pathway).

| Parameter                           | Base value | Range     | Distribution | $\Delta GWP_{100}$ (kg CO <sub>2</sub> eq) |
|-------------------------------------|------------|-----------|--------------|--|
| $I_{elec}$ (g CO <sub>2</sub> /kWh) | 648        | 100-900   | Uniform      | ±155                                       |
| Heat recovery (%)                   | 100        | 0-100     | Uniform      | ±85  |
| Moisture H (%)                      | 7          | 5-30      | Lognormal    | ±28 to ±95                                 |
| $\eta_c$ CHP (%)                    | 25         | 20-32     | Uniform      | ±65  |
| LHV <sup>DM</sup> (MJ/kg DM)        | 15.2       | 14.5-16.0 | Normal       | ±35  |
| $f_{leak}$ CH <sub>4</sub> AD (%)   | 1          | 0.5-6     | Lognormal    | ±245 (AD)                                  |
| BMP (NmL CH <sub>4</sub> /g VS)     | 248        | 180-310   | Normal       | ±38 (AD)                                   |
| $GWP_{100}$ CH <sub>4</sub> (-)     | 27.9       | 27.9-29.8 | Fixed        | ±12 (AD)                                   |



**Fig. 5.** Pareto plot of first-order ( $S_1$ ) and total-order ( $S_t$ ) Sobol indices for  $GWP_{100}$  of the CHP-MA pathway (LHS,  $n = 1000$ ). Error bars = 95 % bootstrap CI.  $I_{elec}$  and heat recovery concentrate 68 % of total explained variance.

The Sobol indices confirm that the carbon intensity of the alternative electricity mix ( $S_1 = 0.42$ ) and the heat recovery rate ( $S_1 = 0.26$ ) together concentrate 68% of the total variance of the  $GWP_{100}$  CHP. Residual moisture ( $S_1 = 0.11$ ) comes in third place, via its influence on the LHV\_WB and thus on the quantities of energy produced (Eq. 1). Total-order indices ( $S_t$ ) confirm the absence of strong higher-order interactions ( $S_t \approx S_1$  for all parameters), validating the near-additive structure of the analytical  $GWP_{100}$  model. These results corroborate the Tornado diagram (Fig. 4b) and converge with the conclusions of similar biomass CHP LCAs in developing-country contexts [10,11,38].

## 5 Discussion

### 5.1 Positioning of results in the LCA literature

Table 5 positions the results of this study in the state of the art of published LCAs on WtE dies with lignocellulosic substrates. The resulting  $GWP_{100}$  CHP (-520 kg  $CO_2eq/t$  TWP in carbon mix) is consistent with the values of Prasara-A & Gheewala (2017) [6] on bagasse (-410 to -510 kg  $CO_2eq/t$ ) in a context of a similar electricity mix (550 vs 648 g  $CO_2/kWh$ ). The residual difference (+40 to +110 kg  $CO_2eq$ ) is explained by the difference in the carbon intensity of the mixes, consistent with the sensitivity  $\Delta GWP_{100}/\Delta I_{elec} = 1.55$  kg  $CO_2eq/t$  per 10 g  $CO_2/kWh$ .

The AD results (-290 kg  $CO_2eq/t$  at 1% leakage) are in the high range of European studies [32], which can be explained by the Moroccan carbon mix amplifying the biomethane substitution credits. Conversely, in the Danish context of Hamelin et al. (2021) [11] ( $I_{elec}$  up to 130 g/kWh), biomethane credits are lower and AD values (-220 to -310 kg  $CO_2eq/t$ ) are in line with our CHP-2030 scenario. This convergence confirms the thermodynamic coherence of the model.

**Table 5.** Positioning of the results in the LCA literature on comparable lignocellulosic substrates.

| substrate  | Stream                   | GWP <sub>100</sub> net<br>(kg CO <sub>2</sub> eq/t DM) | LCA Method        | Database       | Comment  |
|------------|--------------------------|--|-------------------|----------------|--|
| This study | CHP                      | -520   | ReCiPe 2016 H     | ecoinvent 3.10 | mix bass-C MA (648 g CO <sub>2</sub> /kWh); Strong Credit Substitution     |
| This study | AD (f=1 %)               | -290   | ReCiPe 2016 H     | ecoinvent 3.10 | Controlled leaks; competitive vs. carbonated straw                         |
| [7]        | Bioenergy (review)       | -380 to -480   | Multiples         | Multiples      | Generic values from a meta-analysis of bioenergy systems                   |
| [11]       | Hemp biofuel/biogas      | -220 to -310   | ILCD 2011         | ecoinvent 3.0  | Mix DK (130 g/kWh); Smaller credits despite similar substrate              |
| [8]        | AD (manure-based biogas) | -290 to -540   | ReCiPe 2008 H     | ecoinvent 2.2  | Analysis of the energy balances for hemp in Northern Europe.               |
| [38]       | CHP gasification         | -350 to -600   | ILCD 2011         | ecoinvent 3.2  | Quasi-carbon-free DK mix: comparison shows decisive role I <sub>elec</sub> |
| [6]        | CHP                      | -410 to -510   | ReCiPe Midpoint H | Thai grid Data | Mix TH (550 g/kWh); values closest to our MA context                       |

## 5.2 Methodological limitations and validity of conclusions

Several methodological limitations must be acknowledged in this study. First, the absence of experimental primary data specific to Moroccan hemp pressing cake necessitates reliance on bibliographic data for similar substrates; while the resulting  $\pm 15\%$  variability estimated for BMP by cultivar and growing conditions is partially addressed via Monte Carlo analysis, it remains a source of uncertainty that cannot be fully controlled without a dedicated experimental campaign. Second, applying the IPCC convention of a zero GWP100 characterization factor for biogenic CO<sub>2</sub> assumes a closed, short carbon cycle that does not account for recarbonization delays linked to crop rotation [39]. For typical industrial hemp rotation times, the impact of this correction is less than 3% on the net GWP100 CHP and is an accepted limit in the context of this attributional LCA. Finally, a significant methodological limitation lies in the system expansion approach used to quantify substitution credits (Module D). While aligned with the ISO 14044 [16] hierarchy, assigning full displacement credits assumes a static 1:1 substitution of the marginal Moroccan electricity mix. In reality, energy markets are highly dynamic. As the grid rapidly integrates renewable capacities (targeting 52% by 2030), the actual displaced marginal electricity might be less carbon-intensive than the static average mix used in the baseline model. Consequently, the massive climate benefits attributed to the CHP pathway (-520 kg CO<sub>2</sub>eq/t) represent a theoretical maximum that carries a risk of overestimation over the facility's lifespan. Future studies should employ consequential LCA modeling with dynamic long-term marginal mixes to refine these displacement credits

### 5.3 Research perspectives

Three priority research areas emerge: (I) the experimental characterization of Moroccan hemp pressing cake (BMP, LHV, particle size, pollutant content) to reduce parametric uncertainty at the source; (II) the extension of the analysis to other categories of environmental impact insufficiently covered by ReCiPe 2016 in this context (water consumption, impacts on agricultural land, local biodiversity); (III) the development of a social LCA (S-LCA, ISO/TS 14072 standards) integrating the impacts on rural employment and the Moroccan cooperative fabric, a dimension not captured by environmental LCA alone.

## 6 Conclusion

In conclusion, this study, supported by the new opportunities opened by Law No. 13-21 in authorized regions (Taounate, Chefchaouen, Ouazzane, Al Hoceima), demonstrates that CHP is currently the optimal Waste-to-Energy (WtE) pathway for hemp pressing residues in Morocco. Driven by a national electricity mix currently dominated by coal and natural gas, Moroccan CHP cogeneration holds a particularly strong climate advantage, exceeding that of similar technologies in Central Europe or Scandinavia. On a territorial scale, the estimated pressing cake deposit (5000-15000 t TWP/year) represents a substantial GHG avoidance potential of 780-2 340 t CO<sub>2</sub>eq/year in the CHP-MA scenario, offering a direct contribution to the objectives of the National Energy Strategy 2030. However, our findings highlight a critical operational implication for the industry: this advantage captured by the  $f^*(I_{le6})$  analytical relationship will mechanically narrow as Morocco progresses towards its 2030 renewable energy targets. Industrial stakeholders investing today must anticipate this transition. Therefore, we recommend prioritizing CHP for immediate short-term deployment to maximize GHG avoidance, while concurrently integrating strict leak-control protocols (<3.5%) into future Anaerobic Digestion (AD) designs, positioning AD as the dominant sustainable technology for the post-2030 low-carbon grid era. Finally, these estimates must be supported by experimental validation of inventory parameters on regional samples and by an integrated techno-economic analysis

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