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Evaluating Rapeseed Oil as a Cost-Effective and Sustainable Heat Transfer Fluid for Parabolic Trough Collectors in Morocco's Industrial Sector

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Abstract

This study evaluates the performance of rapeseed (colza) oil as a sustainable and cost-effective heat transfer fluid (HTF) for parabolic trough collector (PTC) systems operating in Morocco's industrial sector. Conventional HTFs such as Therminol VP-1 and Delcoterm E15 present environmental and economic drawbacks, including toxicity, high cost, and low biodegradability. Through numerical simulations and experimental validation using the PTMx-24 PTC, this paper compares the thermal properties and performance of rapeseed oil with synthetic oils under Moroccan climatic conditions. Results indicate that rapeseed oil achieves superior outlet temperatures reaching, 220°C in July. Additionally, rapeseed oil demonstrates higher specific heat and thermal conductivity, making it suitable for industrial heat applications. Although its operational lifespan is shorter, its low cost and environmental benefits make it a compelling alternative for sustainable thermal energy systems.

Keywords: Rapeseed oil, parabolic trough collector, heat transfer fluid, thermal performance, Morocco

1. Introduction

Heat transfer fluids (HTFs) are critical components of parabolic trough collector (PTC) systems, determining thermal efficiency, operational temperature range, and overall system performance *(Zhang et al., 2016).* Commercial PTC systems primarily use synthetic HTFs like Therminol VP-1 and Delcoterm E15 for their high-temperature tolerance (up to 400°C) and standardized behavior *(Bellos & Tzivanidis, 2019)*. However, these petroleum-derived fluids present significant disadvantages: high cost (€8-12/liter), poor biodegradability, and ecological hazards (*Delgado-Torres & García-Rodríguez, 2010*).

Recent studies have evaluated the potential of vegetable oils as bio-based HTFs for medium-temperature solar applications, highlighting key advantages such as biodegradability, benign environmental profile, and high heat capacity *(Hoffmann et al., 2018; Gomna et al., 2019, 2020).* Within this category, rapeseed oil has emerged as a particularly promising candidate, offering excellent low-temperature fluidity, favorable viscosity–temperature behavior, and enhanced oxidative stability in the 180–250 °C range—an operating window relevant to industrial SHIP applications. Experimental investigations confirm that rapeseed oil maintains stable thermophysical properties under prolonged thermal exposure *(Gomna et al., 2019, 2020)*, while its performance can be further improved through antioxidant stabilization, extending operational lifetimes under elevated temperatures *(Gertz, 2000; Hoffmann et al., 2018)*. Despite these advantages, studies integrating rapeseed oil into full PTC systems remain scarce, and validated performance data for real solar conditions are still limited.

The Moroccan context further underscores the relevance of exploring rapeseed oil as an HTF. Morocco benefits from a high-quality solar resource, with annual Direct Normal Irradiance (DNI) levels between 2000 and 2600 kWh/m² *(Benbba et al., 2024; Boujoudar et al., 2025),* positioning the country as a strong candidate for solar heat for industrial processes (SHIP). Industrial sectors—particularly agri-food, textiles, and chemical manufacturing—consume over 16.7 TWh of thermal energy annually, with most processes requiring temperatures below 200 °C *(IEA, 2019; IRENA, 2015; Schoeneberger et al., 2020)*. These thermal requirements align well with the stability range of rapeseed oil, reinforcing its suitability for medium-temperature SHIP. Economically Vegetable oils—rapeseed oil in particular—exhibit substantially lower export-market prices compared to synthetic heat-transfer fluids. *(USDA, 2023; Eastman, 2024),* providing a notable cost advantage when used as HTFs in industrial solar heating.

Given the country's abundant solar resource, the growing emphasis on decarbonizing industrial heat, and the need for affordable and environmentally compatible HTFs, assessing the performance of rapeseed oil in PTC systems is both timely and strategically important. This study therefore evaluates rapeseed oil as a cost-effective and sustainable HTF for medium-temperature solar thermal applications in Morocco, providing a comprehensive analysis of its thermo-hydraulic behavior under real DNI conditions and its suitability for industrial process heat supply.

2. Materials and Methods

2.1 PTC System and Mathematical Model

The experimental investigation utilized the PTMx-24 presented in figure 1 PTC at Green Energy Park, Morocco (32.22°N, 7.93°W), with 54.4 m² aperture area and 74.7% optical efficiency. The system produces up to 31 kWth under 900 W/m² DNI. The mathematical model incorporates optical, thermal, and hydraulic sub-models based on energy conservation principles. Heat loss equation parameters and mathematical model are presented in Figure 2 and detailed in *Bouarfa et al. (2024).*):

- Energy Balance: $Q_u = \dot{m}C_p(T_{outlet} - T_{inlet}) = h.A_a.G_{bn}$
- Pressure Drop : $\Delta P = f.\frac{L}{D_{rint}}.(\rho V^2/2)$
- Pumping Power: $W_{pump} = \frac{\dot{m} \cdot \Delta P}{\rho.\eta_{pump}}$

To establish the mathematical formulation, the following simplifying assumptions are adopted:

- The PTC performance is evaluated under steady-state conditions at hourly time steps.
- The heat-transfer fluid (HTF) flow inside the receiver operates in the turbulent regime.
- Soiling effects on the glass envelope (dust and dirt deposition) are neglected.
- The thermo-physical properties of the HTF vary with temperature.
- Heat transfer is considered one-dimensional.
- The absorber and glass envelopes are assumed to experience uniform solar flux, temperature, and thermodynamic properties.
- The PTC employs an east–west tracking configuration.

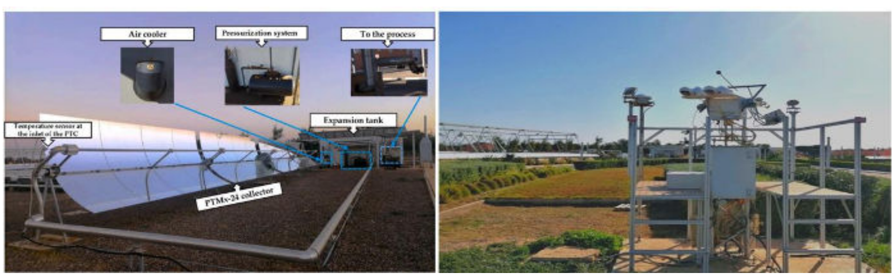

Figure 1: Test Loop PTMX-24 description and meteorological station (Bouarfa et al.,2024)

Heat losses	Equations		
$Q_{lost.1} = Q_{g_{rad}} + Q_{g_{conv}}$	$Q_{g_{rad}} = \pi D_{c_{out}} L \epsilon_{c_{out}} \sigma (T_{c_{out}}^4 - T_{Sky}^4)$		
	$Q_{g_{conv}} = \pi D_{c_{out}} L h_g (T_{c_{out}} - T_{amb})$	$h_g = \frac{Nu_{air} k_{air}}{D_{c_{out}}}$	$Nu_{air} = 0.54 Re_{air}^{0.52} + 0.4$ if $0.1 < Re_{air} < 1000$; $Nu_{air} = 0.3\, Re_{air}^{0.6}$ if $1000 < Re_{air} < 50000$
$Q_{lost.2} = Q_{cond}$	$Q_{lost.2} = Q_{cond} = \frac{2\pi L k_g (T_{c_{int}} - T_{c_{out}})}{\ln \frac{D_{c_{out}}}{D_{c_{int}}}}$		
$Q_{lost.3} = Q_{n_{conv}} + Q_{a.rad}$	$Q_{n_{conv}} = \pi (D_{c_{int}} - D_{r_{out}}) L h_{n_{conv}} (T_r - T_{c_{int}})$	$h_{n_{conv}} = \frac{2k_{ef}}{D_{r_{out}} \ln \frac{D_{c_{int}}}{D_{r_{out}}}}$	
		$k_{ef} = 0.317\, k_{air} (Ra^*)^{1/4}$	
		$(Ra^*)^{1/4} = \left[\frac{\ln(D_{c_{int}}/D_{r_{out}})}{b^{3/4}(1/D_{r_{out}}^{3/5} + 1/D_{c_{int}}^{3/5})^{5/4}}\right] Ra^{1/4}$	
		$Ra = \frac{g\beta(T_r - T_{c_{int}})L^3}{\vartheta \alpha}$	
	$Q_{a.rad} = \frac{\pi D_{r_{out}} L \sigma (T_r^4 - T_{c_{int}}^4)}{\frac{1}{\epsilon_r} + \frac{1 - \epsilon_{ci}}{\epsilon_{ci}} \frac{D_{r_{out}}}{D_{c_{int}}}}$		
$Q_{lost} = Q_{lost.1} = Q_{lost.2} = Q_{lost.3}$			

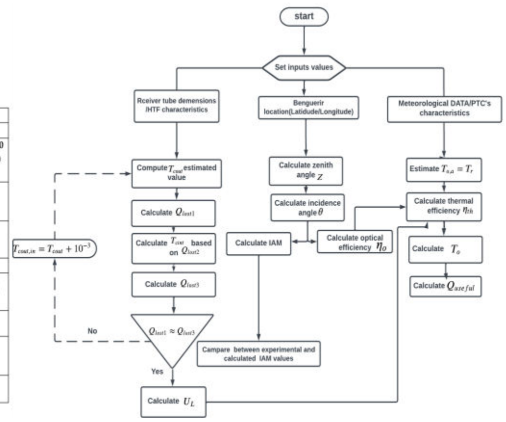

Figure 2: Mathematical model flowchart and heat loss equations parameters

The system works as the following operating conditions:

- DNI 700-950 W/m²,
- inlet temperature 150°C,
- ambient temperature 10-30°C,
- mass flow rate 0.85-1.0 kg/s,
- Reynolds number 2300-15000 (turbulent flow).
- Measurement uncertainties: PT100 RTD ±0.1°C (at 25°C),
- pyrheliometer ±2.0%,
- flowmeter ±1.0%, resulting in combined thermal efficiency uncertainty of ±3.2% using root-sum-square propagation.

2.2 Model Validation

Validation against experimental data yielded: R^2 = 0.985, RMSE = 2.3°C, MAE = 1.8°C, maximum deviation = 3.5°C at peak temperatures. Data from May 17 and July 21 represented spring and summer conditions respectively.

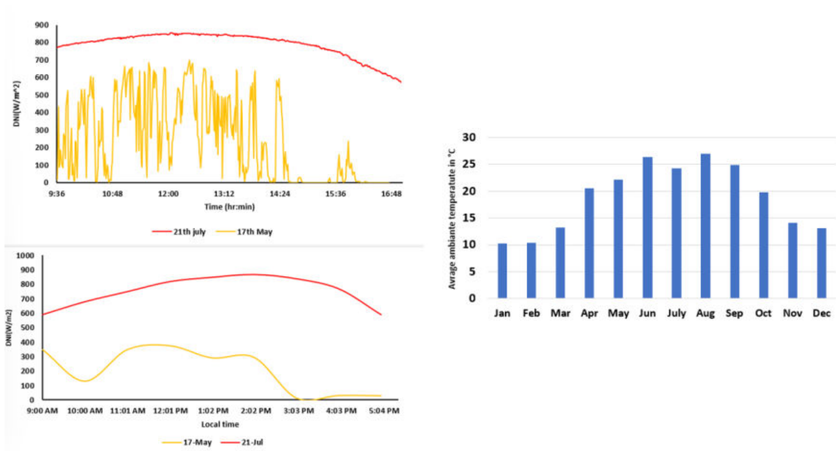

Figure 3: Ambient temperature variations and Direct Normal radiation of 17th May and 21st July

Table 1. Comprehensive HTF Properties and Performance Comparison at 180°C

Property	Rapeseed Oil	Delcoterm E15	Therminol VP-1
Density (kg/m³)	808	745	880
Specific Heat (kJ/kg·K)	2.45	2.48	2.13
Thermal Conductivity (W/m·K)	0.140	0.123	0.114
Dynamic Viscosity (Pa·s)	0.0048	0.0008	0.0007
Max Operating Temp (°C)	230	320	400
Flash Point (°C)	230	182	124
Fire Point (°C)	240	210	127
Cost (€/L)	0.9–1.8	4–7	8–12
Lifespan (years)	2–3	5–7	8–10

3. Results and Discussion

3.1 Thermal Performance Analysis

Figure 4 shows the hourly outlet temperature profiles of rapeseed oil, Delcoterm E15, and Therminol VP-1 for two representative days (17 May and 21 July). Rapeseed oil consistently reaches the highest temperatures, peaking at about 170 °C in May and 220 °C in July, outperforming both synthetic fluids. Therminol VP-1 shows intermediate values, while Delcoterm E15 records the lowest outlet temperatures, particularly during the high summer irradiance of July. However, higher outlet temperatures do not necessarily correspond to better thermal performance. As shown in Figure 4, Delcoterm E15 achieves the highest thermal efficiency, reaching nearly 62%±3.2% despite its lower temperatures. Rapeseed oil shows a modest efficiency advantage because its higher thermal conductivity marginally improves local heat extraction in the thin boundary-layer regime (Figure 5). However, its higher dynamic viscosity increases the local frictional losses.

The results demonstrate that, for demand-driven operation at small module scale, cost and optical/receiver losses largely set performance while hydraulic penalties remain small in absolute power terms but must be carefully considered when scaling.

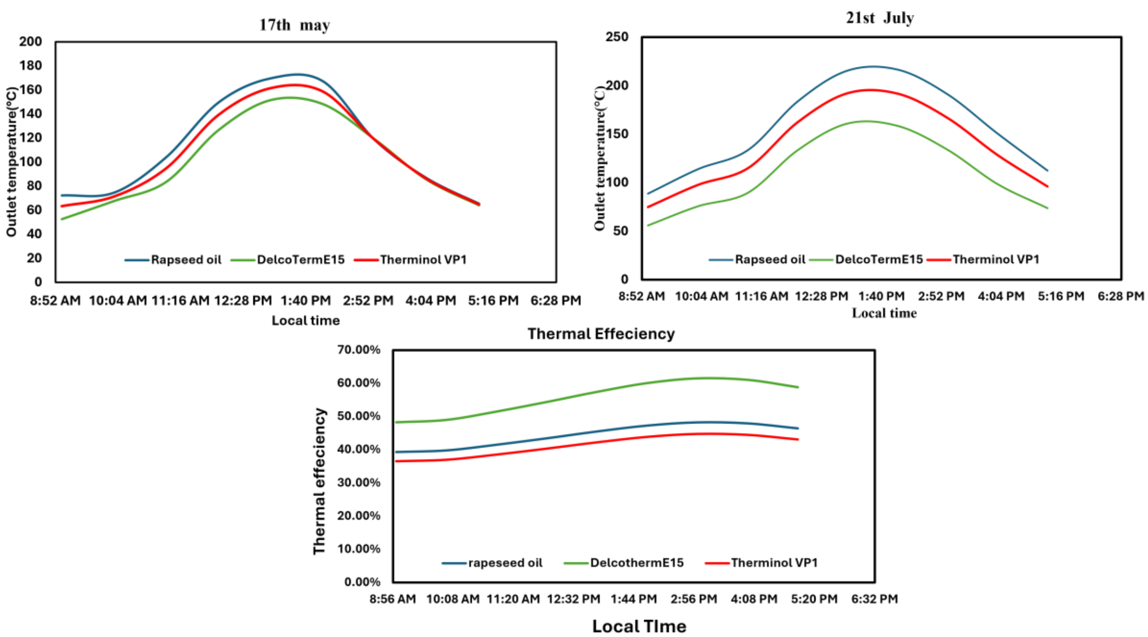

Figure 4: Comparison of outlet temperatures and thermal efficiency for Rapeseed Oil, Delcoterm E15, and Therminol VP-1 under typical spring (17 May) and summer (21 July) climatic conditions

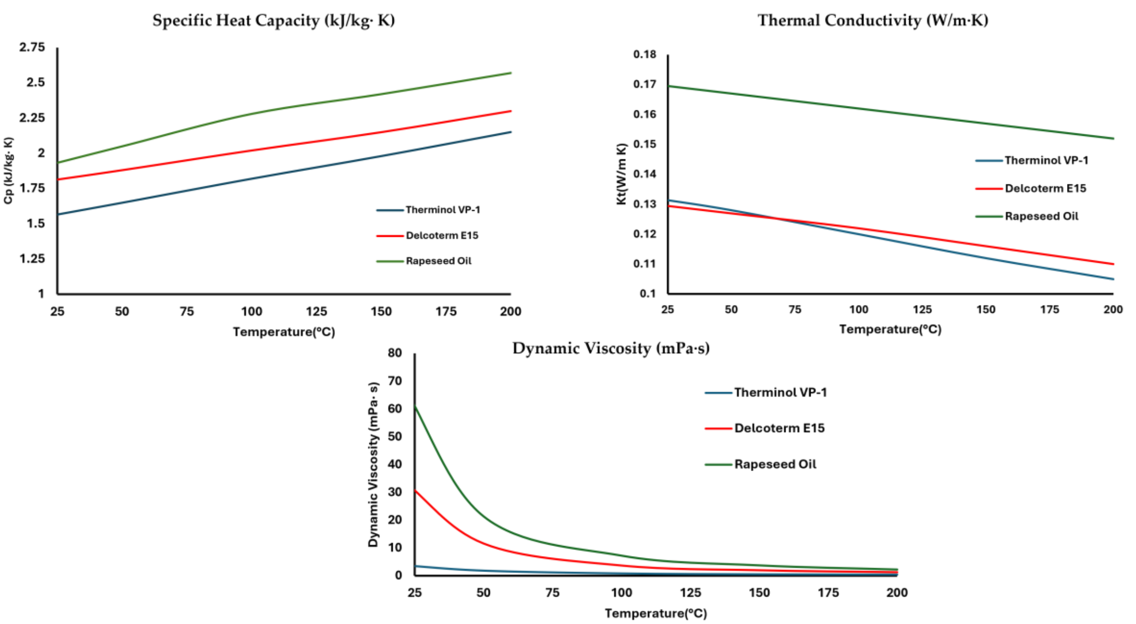

Figure 5: Thermophysical properties for Rapeseed Oil, Delcoterm E15, and Therminol VP-1 under temperature variations climatic conditions

3.2 Pumping Power and Mass Flow Sensitivity

Table2 presents the pumping power requirements at different flow rates. Higher viscosity of rapeseed oil increases pumping requirements by ~206–553 W per 31.5 kW□□, representing only 0.65-1.75% of useful thermal output. Delcoterm E15 and Therminol VP-1 produce lower absolute pumping demands (126–334 W and 116–305 W respectively), representing ~0.40–1.06% and ~0.37–0.97% of thermal output. This minimal penalty does not significantly impact overall system performance.

A sensitivity analysis was performed to evaluate how variations in mass-flow rate affect the hydraulic and thermal response of the PTC system. The pumping power results (Table 2) show that hydraulic demand increases non-linearly with mass flow rate. At 0.50 kg/s, the required pumping power is 206 W for rapeseed oil, 126 W for Delcoterm E15, and 116.3 W for Therminol VP-1. Increasing the flow rate to 0.85 kg/s raises the pumping power to 368.3 W, 225.3 W, and 206 W, respectively, while the highest tested rate (1.00 kg/s) results in 552.5 W for rapeseed oil, 334.4 W for Delcoterm E15, and 305.3 W for Therminol VP-1. These differences stem primarily from viscosity: rapeseed oil exhibits higher dynamic viscosity, leading to greater frictional losses and consequently higher pumping power, especially under high-flow operation.

DNI variability introduces an additional source of uncertainty in the temperature response of the system. The strongly fluctuating DNI on 17 May produces pronounced oscillations in the outlet temperature, with rapid rises and drops reflecting the intermittent solar input. In contrast, the smoother and higher DNI profile of 21 July results in a more stable thermal behaviour, even though outlet temperatures exceed 200–220 °C at low mass-flow rates. A ±15% perturbation in DNI leads to noticeable deviations in the temperature profiles, particularly under low-flow, high-temperature conditions where radiative and convective losses amplify DNI-driven fluctuations. Despite these variations, rapeseed oil maintains stable temperature evolution due to its high heat capacity and gradual thermal response. Overall, the system remains robust under realistic DNI variations, indicating that accurate DNI characterisation is essential for predicting temperature dynamics and ensuring reliable HTF operation.

Table 2. Pumping Power Requirements (W) at Different Flow Rates

Flow Rate (kg/s)	Rapeseed Oil (W)	Delcoterm E15 (W)	Therminol VP-1 (W)
0.50	206.0	126.0	116.3
0.85	368.3	225.3	206.0
1.00	552.5	334.4	305.3

3.3 Long-term Thermal and Oxidative Stability and Degradation of Rapeseed Oil

Rapeseed oil has demonstrated promising thermal and oxidative stability for medium-temperature solar applications, but operation above 180 °C requires careful mitigation and monitoring. Literature reports a <5% viscosity increase after 1000 h at 180 °C, indicating good resistance to thermo-oxidative thickening under that benchmark condition *(Gomna et al., 2019, 2020)*. In the present study outlet temperatures frequently exceed 180 °C (approaching 200–220 °C in peak summer), thus operating near the upper end of the commonly reported stability window. Reported fouling-resistance factors (<0.05 $m^2 \cdot K/kW$ after 18 months at 150–180 °C) suggest comparable fouling behaviour to synthetic oils at moderate temperatures *(Ktistis et al., 2021)*, but extrapolation above 180 °C must be conservative. Oxidative induction times for refined rapeseed oil is short at 180 °C (2.8–3.2 h) but can be extended considerably (to ≈8–13 h) with antioxidant packages; accordingly, closed-loop measures — nitrogen blanketing, 316L stainless steel wetted components, and antioxidant dosing (e.g., 0.5 wt.% TBHQ + 0.2 wt.% citric acid) — are recommended to limit oxidation and prolong service life *(Willing, 2001; Ibsch et al., 2020)*. With these stabilisation strategies and routine monitoring of acid number, viscosity and peroxide value, operational maintenance intervals of the order reported in the literature (≈1000–2000 h) may be achievable; however, pilot-scale ageing above 180 °C remains limited and further validation is required for sustained operation above ~210 °C *(Gertz, 2000; Willing, 2001; Gil et al., 2010).* In short, rapeseed oil is a viable HTF for medium-temperature PTC loops when combined with proven antioxidant and inerting strategies and a tightened monitoring/maintenance plan when operating beyond the 180 °C benchmark.

Table 3: Thermal Safety and Volatility Characteristics of Candidate Heat Transfer Fluids

Property	Rapeseed Oil	Delcoterm E15	Therminol VP-1	Sources
Flash Point	~230°C	~182°C	~124°C	*(Gertz, 2000; Eastman, 2024)*
Fire Point	~240°C	~210°C	~127°C	*(Gertz, 2000; Kumar et al, 2022; Eastman, 2024)*
Auto-Ignition	~363°C	~350°C	~360°C	*(Kumar et.al, 2022; Eastman, 2024)*
Evaporation Loss	Very Low	Moderate	High (due to low boiling point)	*(Eastman, 2024)*

4.1 Total Cost of Ownership (TCO)

Rapeseed oil’s market price (USD 0.90–1.80/kg, *Index Mundi, 2024*) represents only 25–35% of the cost of synthetic HTFs such as Therminol VP-1 (USD 6.00–10.00/kg, *Eastman, 2024*) and Delcoterm E15 (USD 4.00–7.00/kg). Although rapeseed oil requires more frequent replacement (every 2–3 years versus 5–10 years for synthetics), its low acquisition cost, biodegradability, and domestic availability in Morocco make it highly competitive for cost-sensitive SHIP applications. The higher replacement frequency is offset by significantly lower upfront fluid cost and negligible disposal liabilities.

Beyond biodegradability, rapeseed oil's non-toxic classification eliminates specialized handling requirements and emergency response protocols mandated for synthetic hydrocarbon fluids, reducing regulatory compliance costs for industrial operators.

Long-term economic modelling over a 20-year operational period for a 10 MWth system shows that vegetable-oil-based HTFs maintain a substantially lower total ownership cost despite shorter lifetimes. This is consistent with multi-decade field studies indicating that lifecycle economics of bio-based HTFs are dominated by acquisition and disposal savings rather than replacement intervals, especially in distributed industrial systems.

Table 4. Lifecycle Cost Analysis (€)

Cost Component	Rapeseed Oil	Delcoterm E15	Therminol VP-1
Initial HTF	50,000	200,000	400,000
Replacements (total)	300,000	400,000	400,000
Pumping energy (20 yr)	50,000	30,000	28,000
Disposal	5,000	50,000	80,000
Total TCO	**405,000**	**680,000**	**908,000**

4.2 Levelized Cost of Heat (LCOH)

The base-case LCOH values are 42.5 €/MWhth for rapeseed oil, 48.3 €/MWhth for Delcoterm E15, and 52.7 €/MWhth for Therminol VP-1. Sensitivity analysis shows HTF price fluctuations affect LCOH by ±8% for vegetable oils compared to ±15% for synthetic fluids, confirming the superior economic resilience of bio-based options for industrial SHIP deployment.

5. Conclusion

This study demonstrates rapeseed oil's technical and economic viability as a bio-based HTF for medium-temperature PTC systems in Morocco. Despite shorter operational lifespan, rapeseed oil offers: Comparable thermal efficiency below 230°C; Minimal pumping power penalty (0.65-1.75% of output); 55% lower total cost of ownership versus Therminol VP-1; Complete biodegradability and low environmental impact; Local availability supporting energy independence. Results support deployment of rapeseed oil-based HTFs in distributed industrial applications requiring <200°C process heat, particularly:

- **Food processing**: Pasteurization (72-85°C), sterilization (110-130°C), cooking (140-180°C)
- **Textile manufacturing**: Dyeing baths (80-140°C), fabric finishing (120-160°C)
- **Chemical processing**: Reactor jacketing (100-180°C)

For cost-sensitive SMEs in Morocco's agro-food and textile sectors, rapeseed oil provides 90% cost advantage with payback periods under 2 years despite 2-3× replacement frequency.

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