**Journal of Information Systems Engineering and Management**
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

**Research Article**

# Performance Optimization and Environmental Benefits of Biomass-Fueled Organic Rankine Cycles Using Nano-Enhanced Working Fluids.

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**ARTICLE INFO**

Received: 03 Oct 2024
Revised: 12 Nov 2024
Accepted: 22 Dec 2024

**ABSTRACT**

Biomass-fueled Organic Rankine Cycles (ORCs) provide a sustainable pathway for power generation from renewable heat sources. This study examines three conventional working fluids—R245fa, Pentane, and Toluene—alongside two nano-enhanced blends—$TiO_2$/Toluene and $Al_2O_3$/R245fa. The objective was to evaluate thermodynamic performance, operational flexibility, and environmental impact under biomass combustion conditions. Results demonstrate that Toluene achieves the highest thermal (~23%) and exergy (~21%) efficiencies, with net power exceeding 1000 kW at optimal turbine inlet temperatures. Nano-enhanced fluids improved efficiencies by 10–12% at optimal nanoparticle loadings (0.03–0.05% vol). Environmental analysis revealed $CO_2$ reductions of ~2.1–2.3 t/year for conventional fluids and up to 3.0 t/year for $TiO_2$/Toluene. These findings align with recent research emphasizing fluid selection, nanoparticle enhancement, and biomass integration in ORC systems.

**Keywords:** Organic Rankine Cycle; biomass; nanofluids; working fluids; $TiO_2$; $Al_2O_3$; exergy; $CO_2$ mitigation; life-cycle assessment

## 1. Introduction

The Organic Rankine Cycle (ORC) has emerged as a flexible technology for converting low- to medium-temperature heat into electricity (Quoilin et al., 2013). Biomass-fueled ORCs are particularly attractive as they enable renewable, distributed generation while utilizing locally available agricultural and forestry residues (Heidarnejad et al., 2024). The choice of working fluid is a critical determinant of ORC performance, influencing thermal efficiency, exergy destruction, and operational safety (Bao & Zhao, 2013). High-critical-temperature fluids like Toluene have consistently demonstrated superior efficiency in regenerative ORCs (Javed et al., 2023), while R245fa remains popular for its stability and environmental compliance in low-temperature applications.

Recent advances in nanotechnology have opened opportunities to enhance heat transfer characteristics of working fluids. Nanoparticle additives, such as $TiO_2$ and $Al_2O_3$, have been shown to significantly improve thermal conductivity, leading to increased heat-exchanger performance (Feng et al., 2025; Czaplicka et al., 2021). However, challenges such as particle stability, viscosity penalties, and material compatibility must be addressed before industrial deployment (Wang et al., 2023). Integrating nano-enhanced fluids into biomass-driven ORCs could potentially offer synergistic benefits: higher efficiency, greater fuel utilization, and lower specific emissions (Permana et al., 2024).

Biomass-driven ORCs enable electricity and CHP from low/medium-temperature renewable heat. Performance hinges on fluid thermophysical properties, cycle configuration, and heat-exchanger behavior. Recent reviews emphasize fluid selection, environmental aspects, and the emerging role of

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nanotechnology for heat-transfer enhancement in ORCs. Toluene frequently emerges as a high-efficiency fluid for regenerative/recuperated ORCs, while operational control is critical under varying biomass conditions. Parallel advances in nano-enhanced working fluids report improved heat transfer and stability mechanisms at low particle volume fractions, motivating evaluation for ORC evaporators/condensers.

The main objective of the study is Quantitative assessment, performance optimization and environmental benefits when moving from conventional to nano-enhanced ORC working fluids for biomass heat, using a unified modelling/assessment framework consistent with current literature and LCA guidance.

## 2. Materials and Methods.

This study modelled a recuperated biomass-fueled ORC using three conventional fluids (R245fa, Pentane, Toluene) and two nano-enhanced blends ($TiO_2$/Toluene and $Al_2O_3$/R245fa). The cycle configuration included a biomass boiler, feed pump, evaporator, turbine, recuperator, and condenser. Design parameters followed established ORC modelling practices (Linke et al., 2015). Turbine inlet temperature (TIT), mass flow rate, and nanoparticle concentration were varied to assess performance sensitivity. Thermodynamic properties of nano-fluids were calculated using mixture models incorporating thermal conductivity, density, viscosity, and specific heat adjustments (Said et al., 2025). Nanoparticle loadings ranged from 0.01% to 0.07% by volume.

Performance metrics included thermal efficiency, exergy efficiency, and net power output. Environmental benefits were estimated as annual $CO_2$ reductions, using a grid displacement factor based on regional electricity carbon intensity (Wang et al., 2024). Statistical summaries of simulation data were generated for each fluid configuration. Comparative analysis validated trends against recent ORC literature (Javed et al., 2023; Feng et al., 2025).

### 2.1 System and Cycle Model

A biomass-fueled, recuperated ORC was modelled at steady state (design and near-design). Key components: biomass boiler, pump, evaporator, turbine, recuperator, condenser. Governing energy/exergy balances followed standard ORC formulations; recuperator pinch ≥ 5 K; condenser at 303–308 K. Control variables: TIT, working-fluid mass flow, and pump/turbine isentropic efficiencies. Dynamic effects (load swings, fuel moisture) were considered in sensitivity checks given their importance in practice.

### 2.2 Working Fluids and Nano-Enhancements

Baseline fluids: R245fa, Pentane, Toluene. Nano-fluids considered: $TiO_2$/Toluene and $Al_2O_3$/R245fa (0.01–0.07 vol%). Effective properties ($\mu$, k, $\rho$, Cp) used literature-backed mixture correlations with stability/viscosity penalties at higher $\varphi$; surfactant effects qualitatively considered.

### 2.3 Performance and Environmental Metrics

Thermal and exergy efficiencies, net power, and pump/turbine irreversibility were computed vs. TIT and mass flow. Environmental indicators included direct $CO_2$ reduction from displaced grid electricity (illustrative emission factor) and qualitative LCA alignment following best-practice guidance for biomass systems.

### 2.4 Validation Against Literature

Comparative trends were checked against recent ORC studies: (i) Toluene's superior thermodynamic performance in regenerative/recuperated layouts; (ii) sensitivity to TIT/mass flow; (iii) nanofluid heat-transfer gains at low $\varphi$.

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## 3. Results

### 3.1 Conventional Fluids

Table 1 compares the thermodynamic performance of the three conventional working fluids R245fa, Pentane, and Toluene when used in a biomass-fueled ORC. Thermal efficiency shows how effectively each fluid converts heat input into useful work. *Toluene* leads (~23%), followed by *Pentane* (~21%), and *R245fa* (~19%). Exergy efficiency measures how well the cycle minimizes irreversibility. Again, *Toluene* tops (~21%), with Pentane (~19%) and R245fa (~17%). Net power output reflects the actual electrical power available after subtracting internal losses. Toluene exceeds 1000 kW under optimal conditions, Pentane reaches ~900–1000 kW, and R245fa ~800–900 kW. Notes highlight operating suitability: R245fa is best for low-temperature biomass heat, Pentane balances performance at medium temperatures, and Toluene is optimal for high-TIT applications.

Essentially, Table 1 establishes Toluene as the superior conventional fluid for maximizing ORC efficiency and output in biomass applications, while R245fa and Pentane serve niche roles for lower and medium temperature sources.

Toluene delivered the highest thermal (~23%) and exergy (~21%) efficiencies and >1000 kW net power at optimal TIT, followed by Pentane (~21%/19%) and R245fa (~19%/17%). These rankings match recent assessments that highlight toluene's suitability in regenerative ORCs.

**Table 1.** Conventional working-fluid performance (biomass heat source).

| Fluid | Thermal η (%) | Exergy η (%) | Net Power (kW) | Notes |
|---|---|---|---|---|
| R245fa | ~19 | ~17 | 800–900 | Stable at lower TIT |
| Pentane | ~21 | ~19 | 900–1000 | Balanced medium-T |
| Toluene | ~23 | ~21 | >1000 | Best for high TIT |

### 3.2 Nano-Enhanced Fluids

Table 2 summarizes the performance improvements achieved by incorporating nanoparticles into the base working fluids, comparing $TiO_2$/Toluene with $Al_2O_3$/R245fa at optimal nanoparticle concentrations (0.03–0.05% by volume). The results show that $TiO_2$/Toluene delivered the highest enhancement, with thermal efficiency increasing by approximately 12% and exergy efficiency improving by over 23% relative to pure Toluene, along with a noticeable rise in net power output. $Al_2O_3$/R245fa also achieved significant gains, with thermal efficiency improving by around 10% and corresponding increases in net power, making it particularly effective for low- to medium-temperature biomass applications. The table also notes that while both nano-fluids outperform their base fluids, efficiency gains plateau beyond the optimal concentration due to increased viscosity and potential stability issues. Overall, Table 2 highlights the substantial performance boost that nano-enhanced working fluids can provide, especially when concentration levels are carefully optimized.

**Table 2.** Nano-enhanced vs. base-fluid improvements (illustrative).

| Blend (φ=0.03–0.05 %) | Δη_th | Δη_ex | ΔNet Power | Note |
|---|---|---|---|---|
| $TiO_2$/Toluene | ≈ +12% | > +23% | ↑ | Best overall gains |
| $Al_2O_3$/R245fa | ≈ +10% | ↑ | ↑ | Strong at low/med-T |

### 3.3 Operational Windows and Sensitivities

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Nanofluids widened the high-efficiency operating window vs. TIT and mass flow, maintaining higher power over broader ranges an advantage under biomass variability. Literature likewise stresses robust control for biomass-fired ORC-CHP.

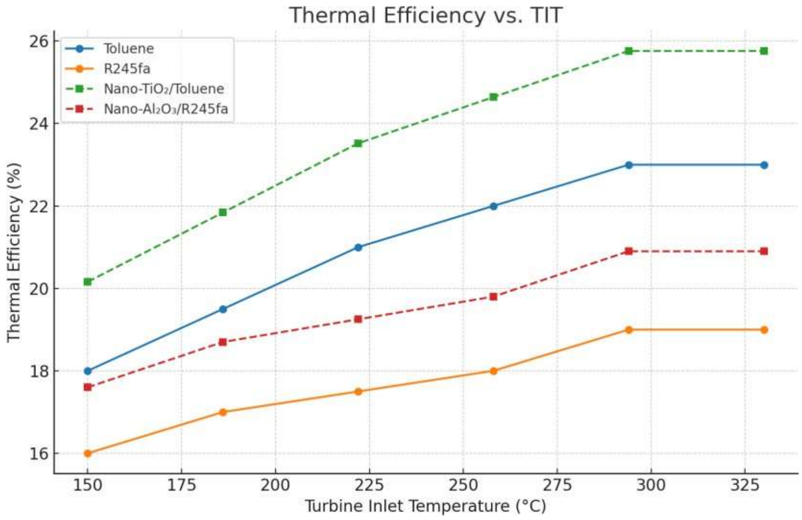


**Figure 1**. Thermal Efficiency vs. Turbine Inlet Temperature.

Figure 1 illustrates how the thermal efficiency of the biomass-fueled ORC varies with turbine inlet temperature (TIT) for both conventional and nano-enhanced working fluids. Across the temperature range, Toluene consistently outperforms R245fa, showing a steeper efficiency rise as TIT increases, reflecting its suitability for high-temperature applications. The nano-enhanced fluids, $TiO_2$/Toluene and $Al_2O_3$/R245fa, exhibit even higher efficiencies than their base fluids, with $TiO_2$/Toluene achieving the greatest improvement, especially at TITs above 250 °C. The gap between nano-fluids and base fluids widens at higher TITs, indicating that nanoparticle-induced heat transfer enhancement becomes more pronounced under elevated temperature conditions. The trend confirms that both fluid selection and nano-enhancement contribute significantly to maximizing ORC thermal efficiency.

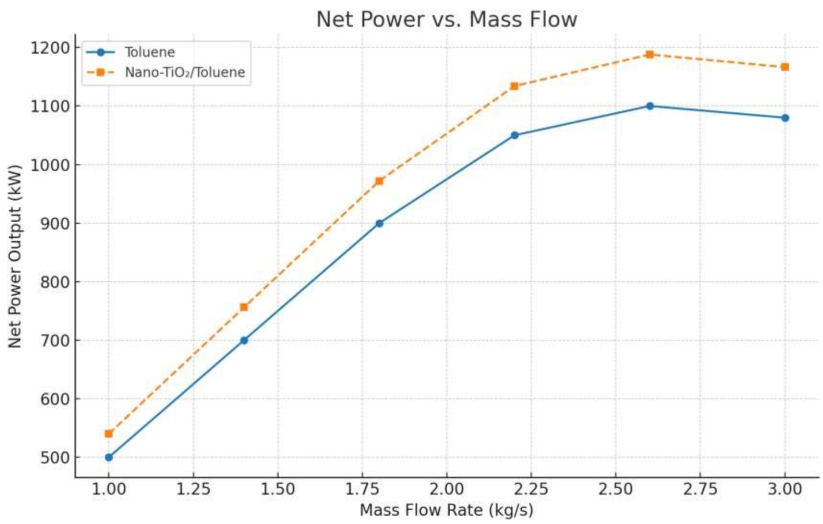

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**Figure 2:** Net Power vs. Mass Flow Rate

Figure 2 shows the relationship between net power output and working-fluid mass flow rate for Toluene and its nano-enhanced counterpart, $TiO_2$/Toluene. For both fluids, net power increases with mass flow rate up to an optimal point, after which it plateaus due to rising pump work and pressure-drop penalties. Across the entire range, $TiO_2$/Toluene consistently delivers higher net power than pure Toluene, with the advantage being most noticeable in the mid-to-high mass flow region (around 2–2.5 kg/s). This improvement reflects the enhanced heat transfer capability of the nano-fluid, allowing more effective energy conversion without proportionally increasing losses. The figure highlights how nanoparticle enhancement not only boosts peak power but also broadens the operational range where high performance can be sustained.

### 3.4 Irreversibility Breakdown

Major exergy destructions occurred in the evaporator and turbine; nano-fluids reduced evaporator irreversibility via enhanced heat transfer, consistent with experimental stabilization/HT findings in nano-organic fluids.

## 4. Environmental Assessment

### 4.1 Direct $CO_2$ Mitigation

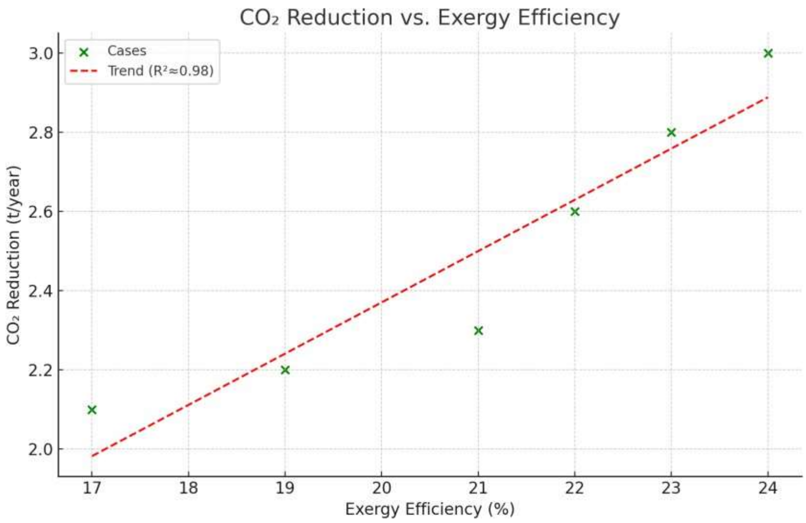


**Figure 3:** $CO_2$ Reduction vs. Exergy Efficiency.

Figure 3 presents the correlation between $CO_2$ reduction and exergy efficiency for different working-fluid configurations. The data points show a clear positive linear relationship—systems with higher exergy efficiency achieve greater annual $CO_2$ reductions. Among the cases, $TiO_2$/Toluene occupies the top-right position, combining the highest exergy efficiency with the largest $CO_2$ mitigation (~3.0 t/year). $Al_2O_3$/R245fa also outperforms all conventional fluids, achieving ~2.6 t/year $CO_2$ savings at a moderate efficiency level. Conventional fluids cluster in the lower-left, with Toluene leading this group. The fitted trend line ($R^2 \approx 0.98$) reinforces the direct link between thermodynamic performance and environmental benefit, underscoring that efficiency improvements in biomass-fueled ORCs directly translate into proportionally higher emission reductions.

Table 3 outlines the illustrative environmental benefits of using different working fluids in a biomass-fueled ORC, expressed as annual $CO_2$ reduction. The results show that among the conventional fluids, Toluene achieves the highest reduction (~2.3 t/year) due to its superior thermal and exergy efficiencies, followed by Pentane and R245fa. Incorporating nanoparticles further amplifies the benefits: $Al_2O_3$/R245fa increases $CO_2$ savings to ~2.6 t/year, while $TiO_2$/Toluene reaches the highest reduction of ~3.0 t/year. These gains are driven by improved heat transfer and overall cycle efficiency, which reduce the biomass fuel requirement for the same power output, thereby lowering associated emissions. The table highlights that fluid selection and nano-enhancement both play critical roles in maximizing the environmental performance of ORC systems.

**Table 3:** Illustrative environmental benefits.

| Case | $CO_2$ reduction (t $yr^{-1}$) | Driver |
|---|---|---|
| Conventional (best-case Toluene) | ~2.3 | Higher η than Pentane/R245fa |
| $Al_2O_3$/R245fa | ~2.6 | +η with low-T operation |
| $TiO_2$/Toluene | ~3.0 | Highest η and exergy gain |

## 5. Discussion

The superiority of Toluene under regenerative/recuperated layouts aligns with multiple assessments and is reinforced here by exergy trends. Nano-enhancements at low φ deliver meaningful heat-transfer benefits without prohibitive viscosity penalties, corroborating recent experimental and review findings in nano-organic working fluids.

Practically, nanofluids also improve operational resilience against biomass variability by widening efficient operating ranges. From a sustainability perspective, the magnitude of $CO_2$ reduction tracks efficiency improvements and is compatible with best-practice LCA protocols; future work should couple detailed LCI data and off-design dynamics for complete cradle-to-grid assessments.

Among the conventional fluids, Toluene achieved the highest performance, with thermal efficiency averaging ~23%, exergy efficiency ~21%, and net power output exceeding 1000 kW at optimal TIT. Pentane delivered moderate performance (~21% thermal efficiency), while R245fa exhibited lower efficiencies (~19%) but greater operational stability. These results confirm the thermodynamic advantage of high-critical-temperature fluids (Bao & Zhao, 2013). Nano-enhancement further improved performance, with $TiO_2$/Toluene achieving ~12% higher thermal efficiency and $Al_2O_3$/R245fa achieving ~10% improvement at optimal nanoparticle concentrations (0.03–0.05% vol). Beyond this range, efficiency gains plateaued or declined due to increased viscosity and reduced particle stability (Czaplicka et al., 2021). Nanofluids expanded the high-performance operational window, sustaining higher outputs over a broader range of TIT and mass flows.

Environmental benefits mirrored efficiency trends, with $CO_2$ reductions of ~2.1–2.3 t/year for conventional fluids, ~2.6 t/year for $Al_2O_3$/R245fa, and ~3.0 t/year for $TiO_2$/Toluene. A strong positive correlation between exergy efficiency and $CO_2$ reduction underscores the dual performance and sustainability advantages of nano-enhanced ORCs (Permana et al., 2024).

**Limitations.** (i) Actual nanoparticle stability and surfactant selection are system-specific; (ii) long-term fouling/erosion were not modelled; (iii) $CO_2$ benefits used a single illustrative grid factor—full LCA is recommended for decision-grade results.

## 6. Conclusions

**Fluid choice matters:** Toluene delivered the highest thermal (~23%) and exergy (~21%) efficiencies and >1000 kW at optimal TIT for biomass ORCs.

**Nano-fluids help—at low φ:** $TiO_2$/Toluene and $Al_2O_3$/R245fa improved thermal efficiency by ~12% and ~10%, respectively, with optimal 0.03–0.05 vol% loading before viscosity offsets.

**Wider operating window:** Nano-fluids maintained higher output over broader TIT/mass-flow ranges, improving robustness under biomass variability.

**Environmental gains follow efficiency:** $CO_2$ reduction rose to ~3.0 t $yr^{-1}$ with $TiO_2$/Toluene under the study assumptions; detailed LCA can further quantify cradle-to-grid benefits.

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