PERFORMANCE EVALUATION OF ENERGY-SAVING SOLUTIONS FOR A THERMAL OIL-BASED DRYING SYSTEM WITH A CAPACITY OF 1000 KG/BATCH

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ABSTRACT

Energy losses in sliced fruit-drying systems employing thermal-oil heaters constitute a critical technical challenge, with measurable impacts on both operational efficiency and environmental performance. This study provides a quantitative assessment of three principal mitigation strategies: 1. Recovery of waste heat from flue gas via installation of an air preheater (APH); 2. Enhancement of insulation and thermal protection; 3.Optimization of the combustion process. When these feasible measures (Solutions 1, 2, and 3) are implemented concurrently, the overall thermal efficiency of the heater can be improved from 87.84% to 95.27%. Building on these results, This study investigates outlines an integrated implementation pathway aimed at maximizing energy utilization efficiency and strengthening the economic performance of fruit-drying operations.

Keywords: *Energy saving, thermal oil heater.*

1. INTRODUCTION

Thermal oil heating systems play an important role in fruit drying processes, particularly in small- and medium-scale agricultural processing lines [1], [2], [3]. Although many studies have addressed the structure and operating characteristics of such systems, quantitative analyses of energy losses and comprehensive frameworks for system optimization remain limited. In practice, boiler efficiency is often reduced due to heat losses through exhaust gases, incomplete combustion, and thermal losses to the surrounding environment. Recent studies have primarily focused on large-scale steam boilers or biomass systems, resulting in a lack of specialized research on thermal oil boilers used in fruit drying applications.

A key research gap lies in the absence of standardized models for evaluating energy efficiency, as well as the lack of integrated analyses combining technical performance and economic efficiency for small- and medium-sized enterprises. In the context of rising energy costs and increasingly stringent emission requirements, the development of energy-saving solutions has become an urgent need [4], [5], [6].

This study aims to analyze and compare different solutions for improving the efficiency of thermal oil boilers based on both technical and economic criteria, thereby identifying optimal solutions for fruit drying systems. The results are expected to provide a scientific basis for investment decisions, system upgrades, and operational optimization [7], [8]. The initial design parameters are as follows [9]:

- Material used for calculations: sliced mango (5 mm thickness), initial moisture content: 85.6%.

- Capacity: 360 kg of fresh sliced mango per batch per drying chamber; the system includes three chambers, corresponding to approximately 1000 kg per batch.

- Drying temperature: 55–65°C; drying time: 6–8 hours; air velocity: 1.5 m/s.

-Ambient air conditions in Ho Chi Minh City: temperature 30°C, relative humidity 80%.

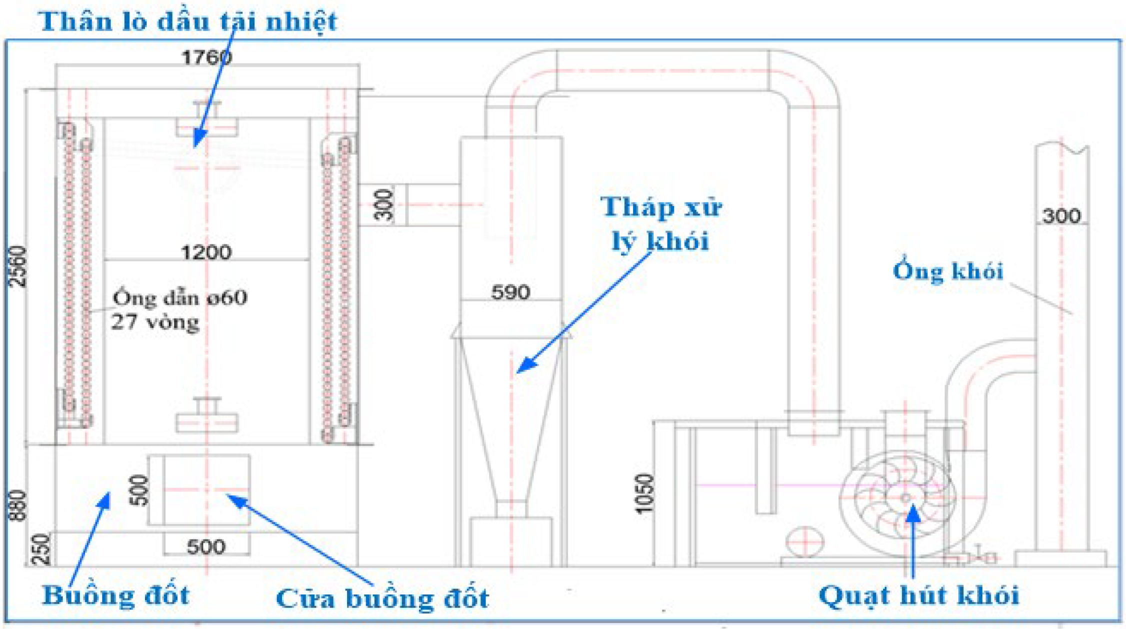

Figure 1. Schematic diagram of the thermal oil boiler system for mango drying

2. CONTENT

2.1. Calculation basis and baseline operating cost

To evaluate the effectiveness of the proposed solutions, the current operating cost of the system is used as the baseline for comparison. Energy balance and boiler efficiency calculations are based on fundamental thermodynamic principles [4], [5], [10], [11]. For a boiler with a capacity of 700 kW, an existing efficiency of 87.84%, and an annual operating time of 4,800 hours, the total annual fuel (coal) cost is estimated at 1,818,768,000 VND.

2.2. Detailed analysis of the proposed solutions

Solution 1: Installation of an air preheater (APH) for waste heat recovery from flue gas

This solution directly targets the largest source of heat loss, namely the flue gas heat loss (q_2). Installing an air preheater (APH) is one of the most common and effective waste heat recovery solutions [12]. By implementing the APH, the flue gas temperature is reduced from 200°C to 150°C, while the combustion air is preheated from 30°C to 95°C [8], [13]–[15].

The theoretical flue gas enthalpy is calculated as:

$$H_{kh} = V_{RO_2} \times (ct)_{RO_2} + V_{N_2}^0 \times (ct)_{N_2} + V_{H_2O}^0 \times (ct)_{H_2O} \tag{1}$$

Using tabulated enthalpy values and interpolation, the average specific heat at 150°C yields [16]

$$H_{kh} = 1{,}404 \times 263{,}75 + 5{,}77 \times 194{,}75 + 0{,}438 \times 227{,}74 = 1593{,}76\ kJ/kg$$

The theoretical air enthalpy is:

$$H_k^0 = V_{kk}^0 \times (ct)_{kk} = 7{,}29 \times 195{,}6 = 1425{,}9\ kJ/kg \quad (2)$$

The actual flue gas enthalpy is calculated as:

A$_b$: The fly ash fraction of the selected fuel, as given in Table 3, is 80% (0.8) [16].

$$H_k = H_k^0 + (\alpha - 1) \times H_{kk}^0 + a_b \times \frac{A^{lv}}{100} \times (ct)_{tr} \quad (3)$$

$$H_k = 1425{,}9 + (1{,}3 - 1) \times 1425{,}9 + 0{,}8 \times \frac{15}{100} \times 125{,}4 = 1868{,}71\ kJ/kg$$

The theoretical air volume is:

$$V_{kk}^0 = \frac{1{,}11 \times Q_t^{lv} + 25 \times W^{lv}}{4168} \quad (4)$$

$$V_{kk}^0 = \frac{1{,}11 \times 26500 + 25 \times 3{,}5}{4168} = 7{,}08\ \mathrm{m^3/kg}$$

The theoretical flue gas volume is:

$$V_k^0 = 0{,}85 \times \frac{Q_t^{lv}}{4168} + 2{,}0 = 0{,}85 \times \frac{26500}{4168} + 2{,}0 = 7{,}4\ \mathrm{m^3/kg}$$

The enthalpy of preheated air $(\alpha \times I_{kk}^0)$ at 95°C

Average specific heat capacity at 95°C with $C_p = 1{,}3\ kJ/m^3N°C$

$$(ct)_{kkl} = C_p \times t = 1{,}3 \times 95 = 123{,}5\ kJ/m^3N \quad (5)$$

Loss calculation q₂

$$q_2 = \frac{[H_k - \alpha \times V_{kk}^0 \times (ct)_{kkl}] \times (100 - q_4)}{Q_t^{lv}}\ \% \quad (6)$$

$$q_2 = \frac{[1868{,}71 - 1{,}3 \times 7{,}08 \times 123{,}5] \times (100 - 1{,}18)}{26500} = \frac{732 \times 98{,}82}{26500} = 2{,}73\ \%$$

Formulas for calculating cost savings and simple payback period (SPP)

$$Cost\ savings\ (VND/year) = C_{year} \times \frac{(q_2 - q_2')}{100} \quad (1)$$

$$Payback\ period\ (year) = \frac{Total\ investment\ cost}{Cost\ savings} \quad (2)$$

Calculation of the new heat loss q_2' (as detailed in the previous section): $q_2' = 2.73\%$

Reduction in heat loss:

$\Delta q_2 = q_2 - q_2' = 7{,}97\% - 2{,}73\% = 5{,}24\%$

Annual cost savings: [7], [17]

1,818,768,000 *VND* x 0.0524 = 95,304,443 *VND*

Estimated investment cost (equipment, installation, insulation): 200,000,000 VND

Simple payback period (SPP):

$$SPP = \frac{200{,}000{,}000}{95{,}304{,}443} = 2.1\ years \quad (3)$$

Result: The flue gas heat loss (q_2) is reduced from 7.97% to 2.73%, corresponding to a 5.24% saving in total energy input. The annual cost savings are estimated at 95,304,443 VND. With an estimated investment cost of 200,000,000 VND, the simple payback period (SPP) is approximately 2.1 years.

Table 1. Performance before and after implementing the optimal solution (APH installation)

Parameter	Before improvement	After improvement
Boiler efficiency (%)	87.84	91.89
Flue gas heat loss (%)	7.97	3.92
Annual fuel cost (billion VND)	1.82	1.73

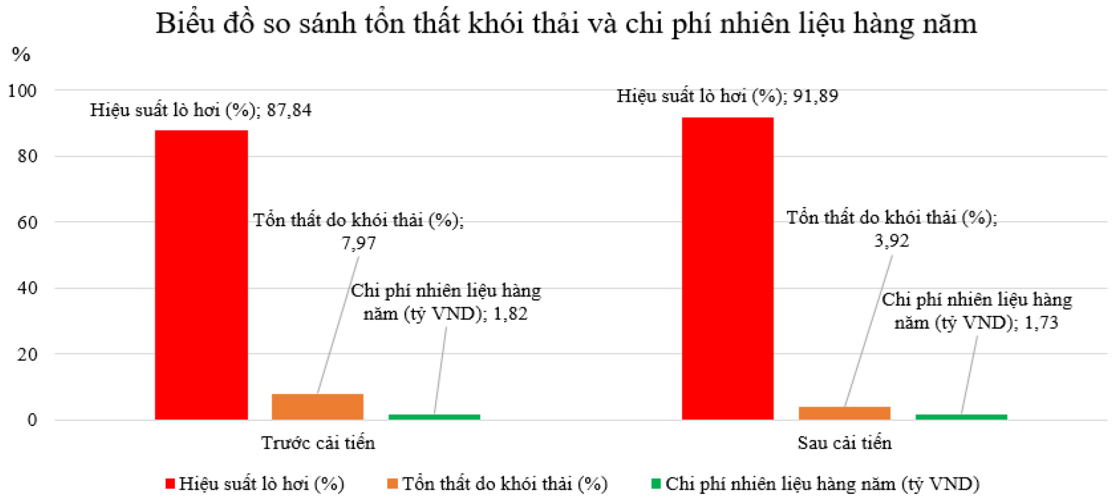

Figure 2. Comparison of flue gas heat loss and annual fuel cost before and after improvement

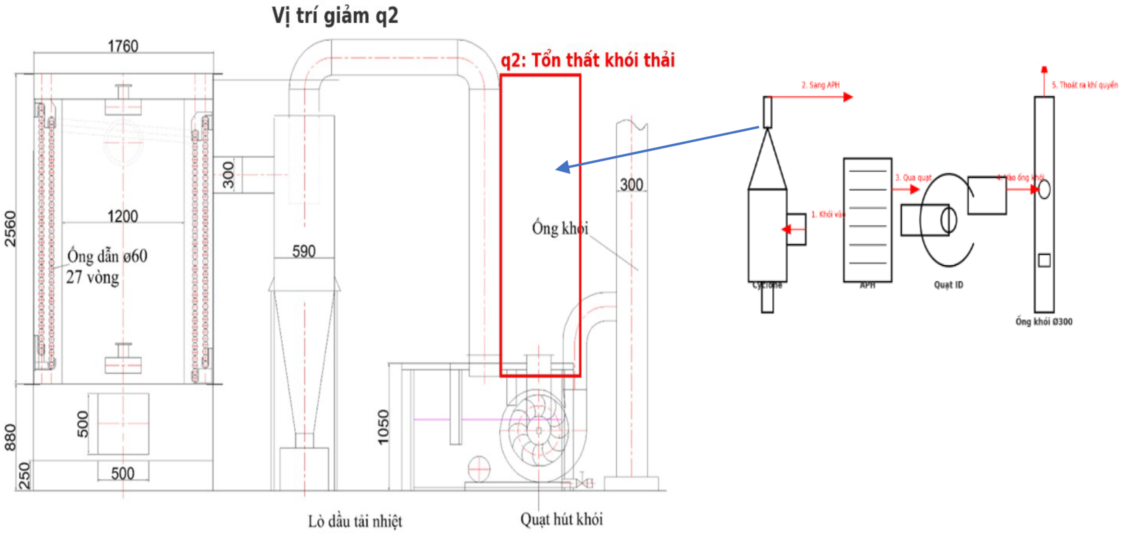

Figure 3. Installation location of the APH in the actual thermal oil boiler

Table 2. Coal price fluctuations in the market

Parameter	Scenario (−10% coal price)	Base case	Scenario (+10% coal price)
Coal price (VND/kg)	3,150	3,500	3,850
Annual savings (VND)	86,640,400	89,156,000	104,671,600
Payback period (years)	2.07	2.02	1.72

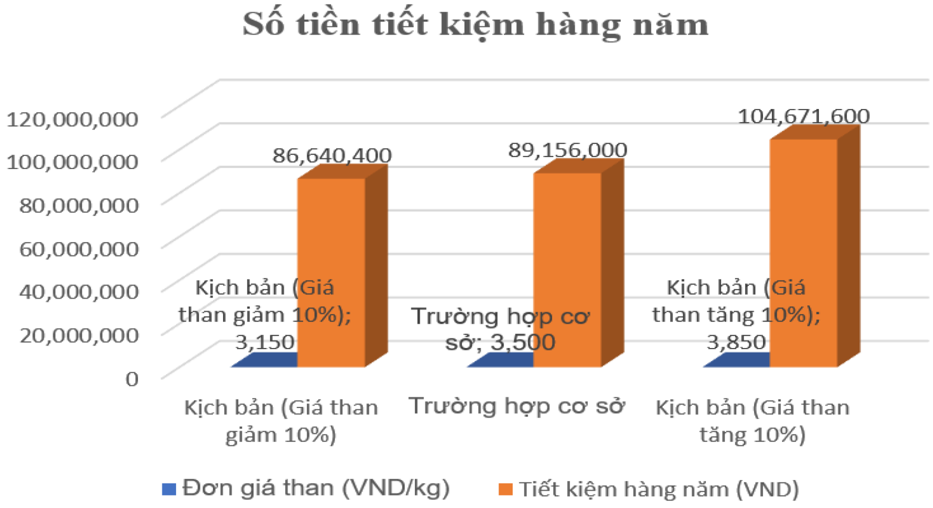

Table 4. Coal price increase and corresponding annual cost savings

Solution 2: Improvement of insulation and thermal protection system

Heat loss to the surrounding environment (q_5) through the boiler walls and piping system represents a significant source of energy waste. Therefore, proper calculation and selection of suitable insulation materials are essential technical requirements [7], [12], [15].

Technical objective: Reduce heat loss q_5 from 2.5% to 1.0%.

Reduction in heat loss:

$\Delta q_5 = 2,5\% - 1,0\% = 1,5\%$

Annual cost savings

1,818,768,000 VND x 0,015 = 27,281,520 VND

Estimated investment cost (materials and labor): 50,000,000 VND

Simple payback period (SPP):

$$SPP = \frac{50,000,000}{27,281,520} = 1.83\ years$$

Economic performance: The annual cost savings are estimated at 27,281,520 VND. With an investment cost of 50,000,000 VND, the payback period is approximately 1.83 years.

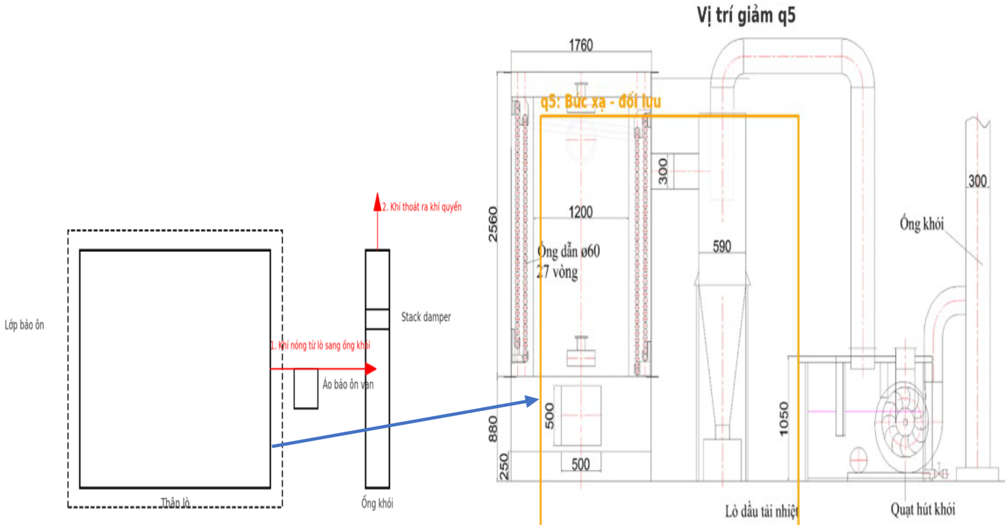

Figure 5. Installation locations of insulation and thermal protection

Solution 3: Optimization of the combustion process

This solution aims to reduce heat losses due to incomplete combustion, both chemical (q_3) and mechanical (q_4). Optimizing the combustion process by precisely controlling the excess air ratio not only reduces energy losses but also contributes to lowering harmful emissions [7], [8], [15].

Technical objective: Reduce heat loss q_3 from 0.42% to 0.21% and q_4 from 1.18% to 0.70%.

$$q_3' = 12600 \times CO \times \frac{V_{k.kh}}{Q_t^{lv}}\ \% \qquad (4)$$

$$q_3' = 12600 \times 0{,}05 \times \frac{8{,}904}{26500} = 0.21\ \%$$

Technical objective: Reduce Cb to 3% and Cx to 7%.

$$q_4 = \frac{326 \times \left(a_x \times \frac{C_x}{100 - C_x} + a_b \times \frac{C_b}{100 - C_b} + a_t \times \frac{C_t}{100 - C_t}\right) \times A^{lv}}{Q_t^{lv}} \times 100 \qquad (11)$$

$$q_4 = \frac{326 \times \left(0{,}2 \times \frac{7}{100 - 7} + 0{,}8 \times \frac{3}{100 - 3} + 0\right) \times 15}{26500} \times 100 = 0.07\ \%$$

Reduction in heat loss:

Δq_3= 0,42% - 0,21% = 0,21%

Δq_4= 1,18% - 0,7% = 0.45%

Total: $\Delta q_{3,4}$= 0.66%

Annual cost savings:

1,818,768,000 VND x 0.0066 = 12,003,869 VND

Estimated investment cost (sensors and control system): 70,000,000 VND

Simple payback period (SPP):

$$SPP = \frac{70{,}000{,}000}{12{,}003{,}869} = 5.83\ years$$

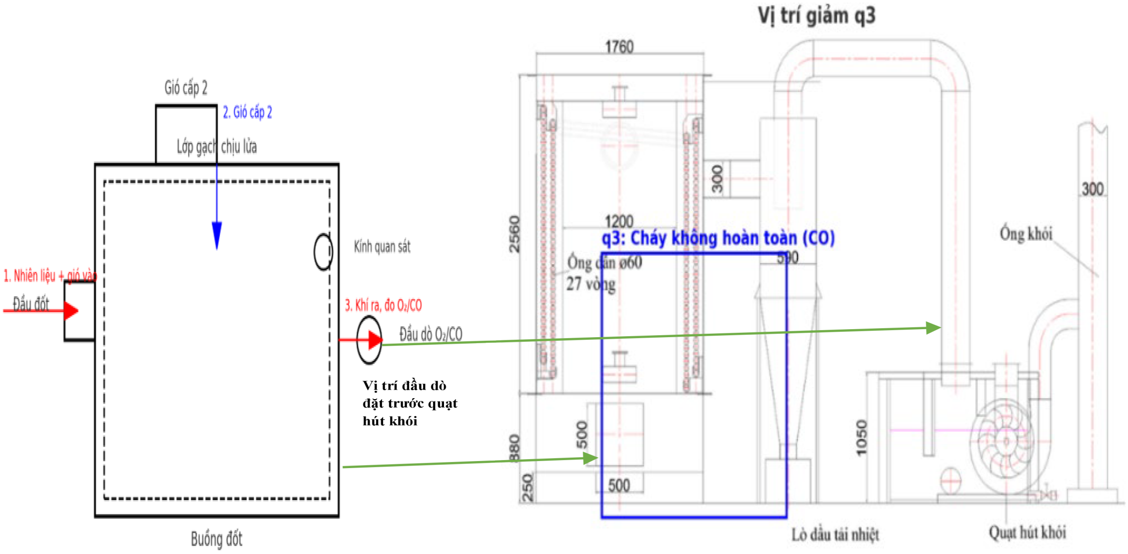

Figure 6. Sensor installation locations for reducing incomplete combustion (CO emissions)

Economic performance: The total annual cost savings are estimated at 12,003,869 VND. However, with an investment cost of 70,000,000 VND, the payback period is relatively long, at approximately 5.83 years.

2.3. Comparison and selection of solutions

Table 3. Comparison of techno-economic performance of the proposed solutions

Criteria	Solution 1 (APH installation)	Solution 2 (Insulation improvement)	Solution 3 (Combustion optimization)
Energy savings (% of total input energy)	5.24%	1.5%	0.66%
Annual cost savings (VND)	95,304,443	27,281,520	12,003,869
Investment cost (VND)	200,000,000	50,000,000	70,000,000
Payback period (years)	2.1	1.83	5.83

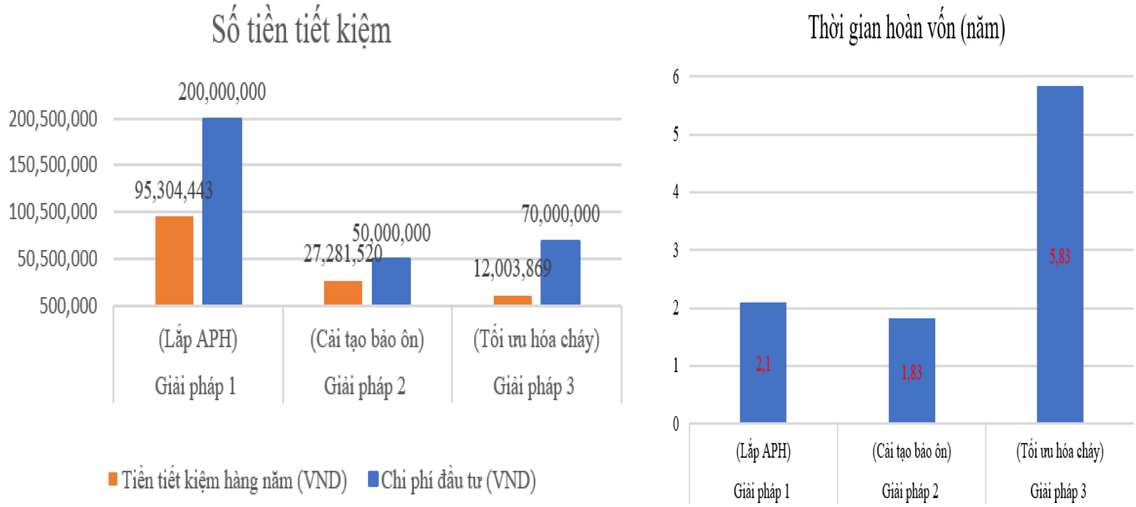

Figure 7. Comparison of investment costs for different solutions

Table 4. Boiler efficiency before and after improvement

Parameter	Symbol	Before improvement	After improvement
Flue gas heat loss	q_2	7.97	2.73
Chemical incomplete combustion loss	q_3	0.42	0.21
Mechanical incomplete combustion loss	q_4	1.18	0.7
Heat loss to the environment	q_5	2.5	1.0
Ash heat loss	q_6	0.09	0.09
Total heat loss	Σq	12.16	4.73
Boiler thermal efficiency	η_1	87.84	95.27

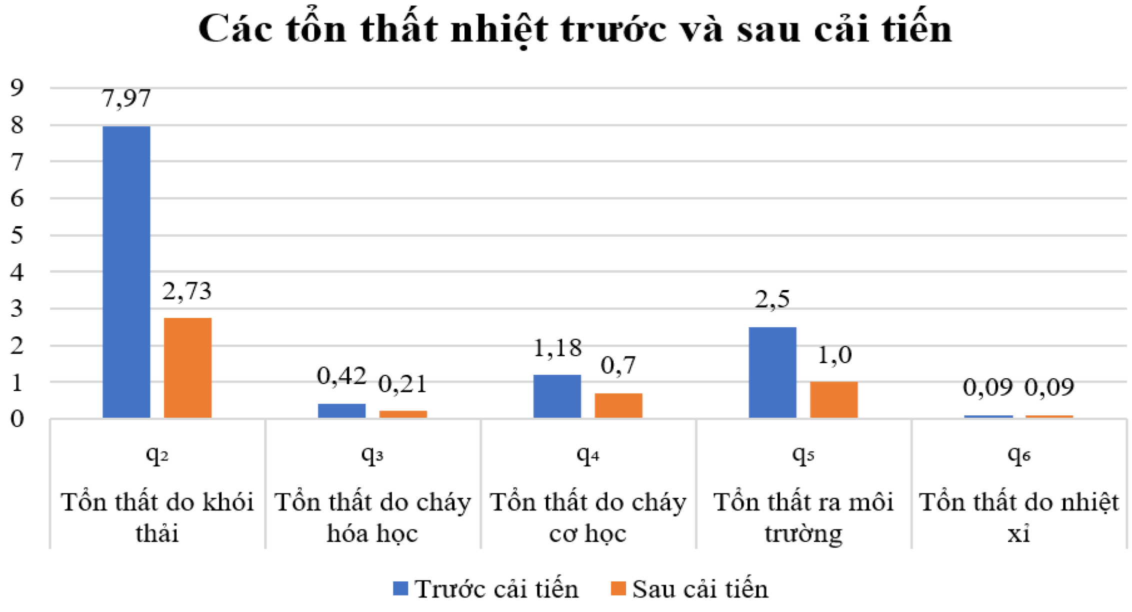

Figure 8. Comparison of heat losses and efficiency before and after improvement

The analysis indicates that Solution 2 has the shortest payback period, making it a "low-investment, quick-return" option. However, Solution 1 delivers significantly higher annual net savings and addresses the largest source of energy loss. In contrast, Solution 3 has the longest payback period and requires more complex operational control.

When all feasible solutions (Solutions 1, 2, and 3) are implemented simultaneously, the overall boiler efficiency can be increased from 87.84% to 95.27%.

3. CONCLUSION

This study identified and quantified the major sources of energy loss in a thermal oil boiler system and evaluated the techno-economic performance of various efficiency improvement solutions. The results demonstrate that both structural improvements and waste heat recovery technologies provide significant benefits. Among them, the installation of an air preheater (APH) has the greatest impact on long-term efficiency. Insulation improvement, on the other hand, is a preferred short-term solution due to its low investment cost and rapid payback period.

A two-stage implementation strategy is proposed. In the first stage, insulation improvements should be applied to achieve immediate efficiency gains. In parallel, preparation for APH installation should be undertaken as the core solution for maximizing energy savings in the medium and long term. The combined application of these solutions can significantly reduce operating costs while supporting sustainability goals.

Future work should focus on extending the study to dynamic thermal modeling of the system, evaluating impacts on equipment lifetime, and analyzing environmental effects. These efforts will contribute to the development of a comprehensive optimization framework for thermal systems in agricultural processing applications.

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