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Technical and Economic Performance Evaluation of Liquid Carbon Dioxide (LCO_2) Cleaning Technology for Electronic Components

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ABSTRACT
This paper presents the research results on liquid carbon dioxide (LCO_2)-based cleaning technology for electronic components, developed as an environmentally friendly solution for high-technology manufacturing industries. The study focuses on evaluating the technical and economic performance of an LCO_2 cleaning system under practical operating conditions. The results demonstrate that LCO_2 technology provides excellent cleaning capability, stable operational performance, and compliance with the stringent cleanliness requirements of high-precision electronic and optical components. Furthermore, the application of this technology contributes to reducing production costs, increasing productivity, and minimizing environmental impacts compared with conventional cleaning methods. The findings confirm the considerable potential of LCO_2 cleaning technology for widespread industrial implementation, supporting the transition toward green and sustainable manufacturing.
Keywords: *Liquid carbon dioxide (LCO_2); electronic component cleaning; surface cleaning technology; technical performance; economic performance; green manufacturing; environmentally friendly technology.*

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I. INTRODUCTION

In high-technology industries such as electronics and optics manufacturing, increasingly stringent surface cleanliness requirements are essential for ensuring product quality and reliability. International standards, including ISO 8501-1:2007 and ASTM D4259, are widely adopted for cleanliness assessment and quality control of cleaned surfaces [1], [6]. However, conventional cleaning methods often generate secondary waste streams, consume significant quantities of chemicals, and may adversely affect both the manufacturing environment and surrounding ecosystems [5].

Liquid carbon dioxide (LCO_2) cleaning technology has emerged as an advanced cleaning solution due to its ability to effectively remove surface contaminants without leaving residual deposits after treatment. According to studies conducted by the Fraunhofer Institute and NASA, this technology offers several advantages, including the elimination of hazardous solvents, the absence of wastewater generation, and compatibility with high-precision electronic components and sensitive optical devices [3], [4]. In addition, numerous SCI-indexed publications published between 2015 and 2023 have demonstrated that LCO_2 cleaning technology can significantly improve surface cleanliness while satisfying the requirements of environmentally sustainable and green manufacturing processes [2], [5].

Based on these considerations, this study evaluates both the technical and economic performance of LCO_2-based cleaning technology for electronic components under actual production conditions. The investigation focuses on cleaning effectiveness, operational stability, and the potential applicability of the technology to electronic and optical components. The research findings provide a scientific basis for the adoption and wider implementation of LCO_2 cleaning technology within the electronics manufacturing and precision engineering industries in Vietnam, thereby contributing to the advancement of sustainable industrial production practices [7].

II. ECONOMIC PERFORMANCE EVALUATION

2.1. Theoretical Basis for Economic Evaluation

The economic performance of LCO_2 cleaning technology was evaluated based on several key indicators, including operating costs, material savings, degree of automation, and long-term investment efficiency. During practical operation, the system demonstrated a significant reduction in chemical consumption while eliminating expenses associated with wastewater treatment and industrial waste management [5]. These advantages contribute to both environmental protection and improved manufacturing efficiency.

The following economic indicators were considered:

- Cost per unit cleaning area;
- Total operating cost;
- Return on Investment (ROI);
- Life Cycle Cost (LCC).

The cleaning cost per unit area is determined as:

$$C = (C_{CO2} + C_{energy} + C_{labor} + C_{maintenance}) / A$$

where:

- C: Cleaning cost (VND/m²);
- CCO_2: CO_2 consumption cost;
- Cenergy: Electricity cost;
- Clabor: Labor cost;
- Cmaintenance: Maintenance cost;
- A: Effective cleaning area (m²).

In addition, investment efficiency was assessed using the Return on Investment (ROI), defined as the ratio of net benefit generated by the system to the total investment cost over the evaluation period.

2.2. Cleaning Cost Analysis of the LCO_2 System

Based on experimental operating conditions, the following parameters were adopted for economic calculations:

- CO_2 consumption rate: 100 g/min;
- CO_2 price: 15,000 VND/kg;
- Cleaning productivity: 0.2 m²/min;
- Electrical power consumption: 1 kW;
- Labor cost: 50,000 VND/h.

The estimated operating costs include the CO_2 consumption cost, the electricity cost, and the maintenance cost. The total cleaning cost can therefore be expressed as:

$$C_{total} = C_{CO2} + C_{energy} + C_{labor} + C_{maintenance} \approx \mathbf{12{,}800\ VND/m^2}$$

This result indicates that the proposed technology can provide competitive cleaning costs while maintaining high cleaning quality and environmental compatibility.

2.3. Comparison with Conventional Cleaning Technologies

Table 1 presents a comparison between the proposed LCO_2 cleaning technology and several conventional cleaning methods.

Table 1: Comparison of LCO_2 cleaning technology with conventional cleaning methods

Cleaning Method	Cost (VND/m²)	Cleanliness Level	Environmental Impact	Remarks
LCO_2 cleaning technology	~12,800	Sa3	Environmentally friendly	Optimal performance
Manual cleaning	15,000–25,000	Low	Inconsistent	Highly operator-dependent
Sand blasting	20,000–40,000	Sa2.5–Sa3	High dust generation	Surface abrasion may occur
Dry ice blasting	25,000–50,000	Sa3	Good	Relatively high operating cost
Chemical cleaning	18,000–30,000	Sa2–Sa3	Hazardous waste generated	Requires wastewater treatment

The comparison demonstrates that LCO_2 cleaning technology reduces cleaning costs by approximately 20–50% compared with conventional alternatives. Furthermore, it achieves the highest cleanliness level while maintaining excellent environmental performance.

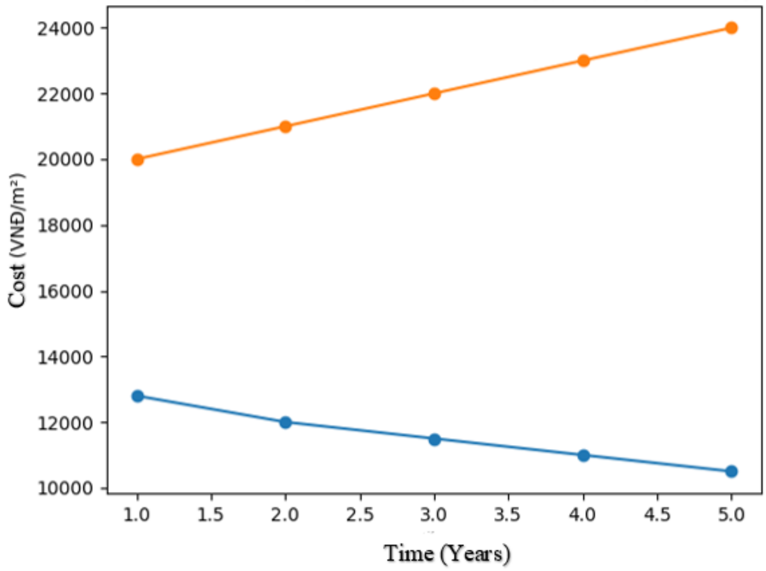

Figure 1: Variation in cleaning costs over time between LCO_2 technology and conventional cleaning methods

The results indicate that the cleaning cost associated with LCO_2 technology gradually decreases over time due to operational optimization and equipment depreciation. In contrast, traditional methods tend to experience increasing costs as a result of labor expenses, consumable materials, and environmental treatment requirements. These findings confirm the superior long-term economic benefits of LCO_2 cleaning technology [11].

2.4. Investment Efficiency

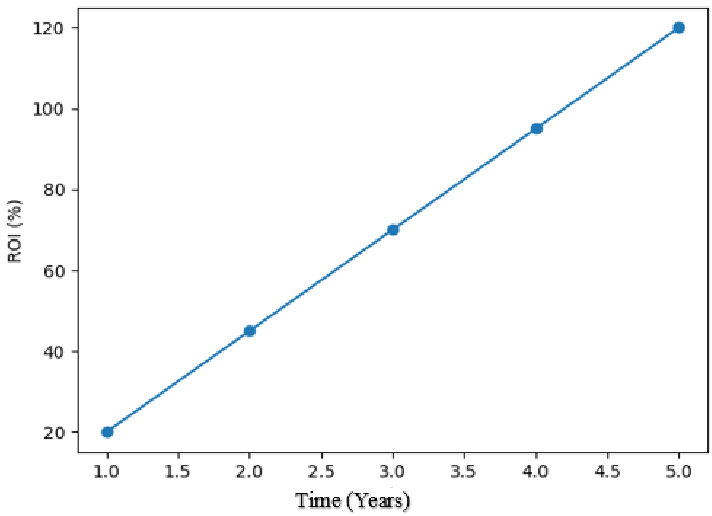

Figure 2: Return on Investment (ROI) trend of the proposed system

The developed LCO_2 cleaning system was designed using a significant proportion of domestically manufactured components, resulting in an equipment cost approximately 60% lower than comparable imported systems [11].

Assuming an operating cost reduction of approximately 30%, the estimated payback period is 1.5–2.5 years.

The ROI analysis indicates that the investment efficiency increases rapidly during operation and exceeds 100% after approximately 4–5 years. This result demonstrates the long-term economic feasibility of LCO_2 technology compared with conventional cleaning methods.

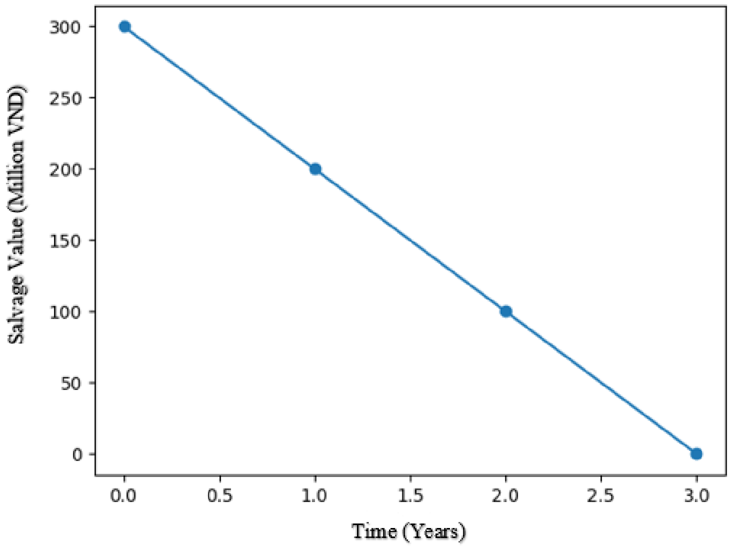

Figure 3: Payback period of the developed LCO_2 cleaning system

The investment cost can be recovered within approximately 1.5–2.5 years, which is consistent with both theoretical calculations and industrial case studies. Such a short payback period represents a significant advantage when making investment decisions.

2.5. Manufacturing Performance

The implementation of LCO_2 cleaning technology provides several production-related benefits:

- Productivity improvement of approximately 20–30% due to automation of the cleaning process and the integration of a three-axis positioning fixture, which reduces cleaning time;
- Reduction in labor requirements by approximately 30–50%;
- Lower operating costs through the elimination of cleaning chemicals, reduced maintenance requirements, and the absence of wastewater treatment costs;
- Reduced product defects, resulting in improved component quality and lower rejection rates.

Further optimization of nozzle design and spraying parameters is recommended to minimize CO_2 consumption, which remains the primary operating cost of the technology.

2.6. Environmental and Indirect Economic Benefits

In addition to direct economic advantages, the technology provides substantial environmental benefits:

- No wastewater treatment costs;
- No generation of hazardous chemical residues;
- Reduced long-term environmental management costs;
- Compliance with urban environmental regulations and green manufacturing policies.

These characteristics make LCO_2 cleaning technology particularly suitable for sustainable industrial development and environmentally responsible manufacturing.

2.7. Overall Economic Assessment

Table 2 summarizes the overall economic performance of the proposed technology.

Table 2: Overall economic performance assessment of the LCO_2 cleaning system

Criterion	Assessment
Cleaning cost	Competitive, ~12,800 VND/m², lower than conventional methods
Investment efficiency	ROI exceeds 100% after approximately 4–5 years
Payback period	Approximately 1.5–2.5 years
Operating cost	Reduced through automation and elimination of chemical/wastewater costs
Sustainability	High; no hazardous residues, compliant with green manufacturing policies

Overall, the proposed LCO_2 cleaning technology not only achieves excellent technical performance but also offers significant economic advantages, particularly in long-term industrial applications. Compared with conventional cleaning methods, the technology demonstrates clear superiority in terms of operating cost, environmental sustainability, and automation capability, making it highly suitable for future green manufacturing strategies [4], [6].

III. TECHNICAL PERFORMANCE EVALUATION

3.1. Evaluation Based on Experimental Results

a) Assessment of Technical Performance Indicators

The technical performance of the developed LCO_2 cleaning system was evaluated through experimental testing and verification against the project objectives.

Table 3: Technical performance indicators of the LCO_2 cleaning system

Performance Indicator	Target / Design Value	Achieved Result
Surface cleanliness	Sa3	Sa3
CO_2 consumption rate	≤ 70 g/min	58–66 g/min
Cleaning productivity	≥ 0.10 m^2/min	0.10–0.258 m^2/min
Spray distance	10–30 mm	10–30 mm (optimal range achieved)
Control channels	2 channels	2 channels

Discussion:

The experimental results demonstrated that the developed system successfully achieved the target cleanliness level of Sa3, satisfying the project requirements. The obtained results are considered reliable because the cleaning system underwent technical verification and calibration before testing.

Furthermore, the measured cleaning productivity exceeded the initial design specification, while CO_2 consumption remained within the expected range. Consequently, the overall cleaning cost was reduced and cleaning time was shortened, improving operational efficiency.

b) Compliance with Technical Requirements

The capability of the LCO_2 cleaning technology to satisfy industrial cleaning requirements was assessed as follows:

Table 4: Compliance of the LCO_2 cleaning technology with industrial requirements

Technical Requirement	Required Level	Achieved Result	Assessment
No component damage	Mandatory	Achieved	Pass
No residual contamination	Mandatory	Achieved	Pass
Removal of fine dust from computers, cameras, and mobile devices	> 95%	> 95% (Sa3)	Pass
Removal of oil and polymer residues	Complete	Complete	Pass
Operational stability	Continuous operation	Stable continuous operation	Pass

The results indicate that the developed technology fully satisfies the requirements for cleaning high-precision electronic and optical components. No physical damage, scratches, or residual contamination were observed after cleaning.

c) Evaluation of Research Deliverables

The quantity and quality of the research outputs were assessed against the project objectives.

Table 5: Evaluation of research deliverables

Deliverable	Target	Achieved Result	Assessment
LCO_2 cleaning system	01 system	01 system	Achieved
Spray nozzle assemblies	02 types	Complete	Achieved
Three-axis positioning fixture	01 set	Complete	Achieved
Scientific report	Complete set	Complete	Achieved

All planned deliverables were successfully completed and met the required technical specifications.

d) Comparison with International Technologies

A comparison between the developed LCO_2 cleaning system and representative international technologies is presented in Table 6.

Table 6: Comparison between the developed system and international technologies

Criterion	Developed System	International Systems
Surface cleanliness	Sa3	Sa2.5–Sa3
CO_2 consumption	58–66 g/min	30–400 g/min
Productivity	0.10–0.25 m²/min	0.10–0.30 m²/min
Control system	2 channels	2–4 channels
Automation	Three-axis positioning system	Available
Equipment cost	~60% of imported systems	100%

The developed LCO_2 cleaning system demonstrates technical performance comparable to internationally available equipment in terms of cleanliness level, cleaning productivity, and CO_2 consumption rate.

A significant advantage of the proposed system is its lower manufacturing cost, estimated at approximately 60% of equivalent imported equipment, while maintaining comparable technical performance [11].

e) Evaluation Under Industrial Operating Conditions

The developed cleaning technology was tested in practical industrial environments, including:

- Electronic motor and component cleaning at Nam A Mechanical and Electrical Joint Stock Company;
- Cleaning of electrical cabinets, electronic equipment, and production-line components at industrial service enterprises;
- Cleaning of optical lenses and camera components at Tamron Optical Vietnam Co., Ltd.

The experimental applications demonstrated that the developed LCO_2 cleaning system:

- Operated reliably and continuously;
- Was easily integrated into existing production lines;
- Caused no product defects;
- Reduced operating costs while increasing productivity.

These results confirm the feasibility of industrial-scale implementation of the developed technology.

3.2. Evaluation of Industrial Deployment Performance

a) Case Study: Kim Viet Phat Technology Development Co., Ltd.

Application Characteristics

Target products: Optical lenses; lens assemblies; precision components.

Technical requirements: Extremely high cleanliness level (Sa3); no scratches; no residual contamination.

Table 7: Performance Before LCO_2 Implementation

Parameter	Value
Cleaning method	Manual wiping with solvents
Productivity	~0.12 m²/min
Cleaning cost	~25,000 VND/m²
Labor requirement	2–3 operators
Product defect rate	3–5%
Environmental condition	VOC emissions requiring treatment

Table 8: Performance After LCO_2 Implementation

Parameter	Value
Cleaning method	Automated LCO_2 cleaning
Productivity	~0.258 m²/min

Cleaning cost	~12,800 VND/m²
Labor requirement	1 operator
Product defect rate	0%
Environmental condition	Clean and environmentally safe

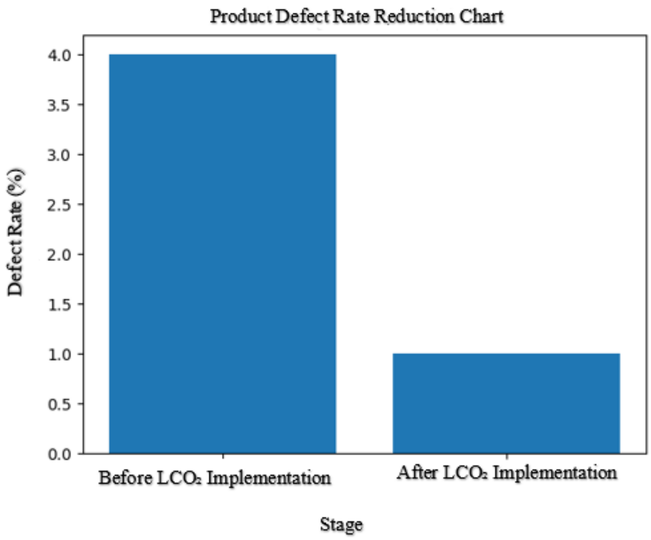

Figure 4: Comparison of product defect rates before and after the implementation of LCO_2 cleaning technology

Results

The implementation of LCO_2 technology reduced cleaning costs by:

$$\mathbf{\Delta C = 25{,}000 - 12{,}800 = 12{,}200\ VND/m^2}$$

→ Corresponding to approximately **49% cost reduction**.

The product defect rate decreased from approximately 4% to 0%, significantly improving product quality and reducing manufacturing losses.

Assuming a cleaning area of 50 m²/day and 300 operating days per year, the annual savings are estimated as:

$$\mathbf{50 \times 300 \times 12{,}200 = 183{,}000{,}000\ VND/year}$$

With an estimated equipment investment of approximately 300 million VND, the payback period is approximately 1.5–2 years.

These results indicate substantial economic benefits and confirm the suitability of the technology for precision optical manufacturing.

b) Case Study: Nam A Mechanical and Electrical Joint Stock Company

Application Characteristics

Target products:

- Electric motors;
- Electrical components.

Technical requirements:

- Removal of oil contamination and industrial dust;
- Preservation of electrical insulation properties.

Table 9: Performance Before LCO_2 Implementation

Parameter	Value
Cleaning method	Chemical cleaning and manual wiping
Cleaning cost	~20,000 VND/m²
Productivity	~0.15 m²/min
Labor requirement	2 operators
Product defect rate	>5%

Table 10: Performance After LCO_2 Implementation

Parameter	Value
Cleaning method	LCO_2 cleaning
Cleaning cost	~13,000 VND/m²
Productivity	~0.20 m²/min
Labor requirement	1 operator
Product defect rate	0%

Results

The implementation of LCO_2 technology resulted in:

- Approximately 35% reduction in cleaning costs;
- Approximately 33% increase in productivity;
- Reduction of product defects from more than 5% to 0%.

Assuming a cleaning area of 40 m²/day and 300 operating days per year, the annual cost savings are estimated at:

$$40 \times 300 \times 7{,}000 \approx 84{,}000{,}000 \text{ VND/year}$$

The results confirm the suitability of the technology for industrial and electromechanical manufacturing environments.

c) Overall Technical Assessment

Table 11: Overall comparison of industrial deployment performance

Criterion	Kim Viet Phat	Nam A	Assessment
Cost reduction	~49%	~35%	Very high
Productivity improvement	~83%	~33%	Significant
Defect reduction	Very high	High	Important
Payback period	~1.5–2 years	~2–3 years	Rapid

Theoretical analysis, cost calculations, and industrial testing collectively demonstrate that LCO_2 cleaning technology provides superior technical and economic performance compared with conventional cleaning methods [3], [9].

The technology shows strong potential to replace traditional cleaning processes and can be widely implemented in industries such as electronics manufacturing, optical component production, precision engineering, and electromechanical assembly.

Overall, the developed system achieves technical performance comparable to international technologies in terms of cleanliness level, productivity, and CO_2 consumption while offering a significant cost advantage. The integration of automation, reduced cleaning time, lower labor requirements, and elimination of product defects contribute to enhanced production efficiency and improved product quality.

Compared with conventional cleaning methods, LCO_2 technology provides superior sustainability, lower long-term operating costs, and improved environmental compatibility. These advantages support cleaner production practices and align with the development objectives of modern green manufacturing industries.

IV. CONCLUSIONS

This study presented a comprehensive technical and economic evaluation of liquid carbon dioxide (LCO_2) cleaning technology for electronic and optical components. The quantitative analyses, supported by productivity, operating cost, and investment-performance assessments, demonstrate that the proposed technology not only satisfies stringent technical cleanliness requirements, achieving a surface cleanliness level equivalent to Sa3, but also provides significant economic advantages compared with conventional cleaning methods, particularly in large-scale industrial applications [11].

The industrial validation conducted at two collaborating enterprises confirmed the practical effectiveness of the developed LCO_2 cleaning system. The technology demonstrated excellent contaminant removal capability, reduced operating costs, improved production efficiency, and significantly lowered product defect rates. The results indicate that the implementation of LCO_2 cleaning technology can contribute substantially to quality improvement and manufacturing cost optimization.

Experimental cleaning tests performed on various electronic devices and components, including mobile phones, cameras, and computer-related equipment, further verified the effectiveness of the proposed technology. The results confirm that LCO_2 cleaning technology offers high economic value, reliable operational performance, and strong potential for commercial deployment in industrial manufacturing environments.

Compared with conventional cleaning techniques, the developed LCO_2 system provides several notable advantages, including reduced chemical consumption, elimination of wastewater generation, lower labor requirements, enhanced automation capability, and improved environmental sustainability. These characteristics make the technology particularly suitable for modern green manufacturing and cleaner production strategies.

Furthermore, industrial implementation demonstrated that the developed LCO_2 cleaning technology reduced product defect rates from approximately 4–5% to 0%, highlighting its effectiveness in improving product quality and manufacturing reliability [11].

Overall, the research findings demonstrate that LCO_2 cleaning technology is a technically feasible, economically viable, and environmentally friendly solution for the cleaning of high-precision electronic and optical components. The technology exhibits strong potential for broader industrial adoption within the electronics, optics, precision engineering, and electromechanical manufacturing sectors in Vietnam, thereby supporting the transition toward sustainable industrial development and advanced manufacturing practices.

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