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Life-Cycle Assessment of PA66 Composite Piston Rings: Environmental and Performance Evaluation

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ABSTRACT

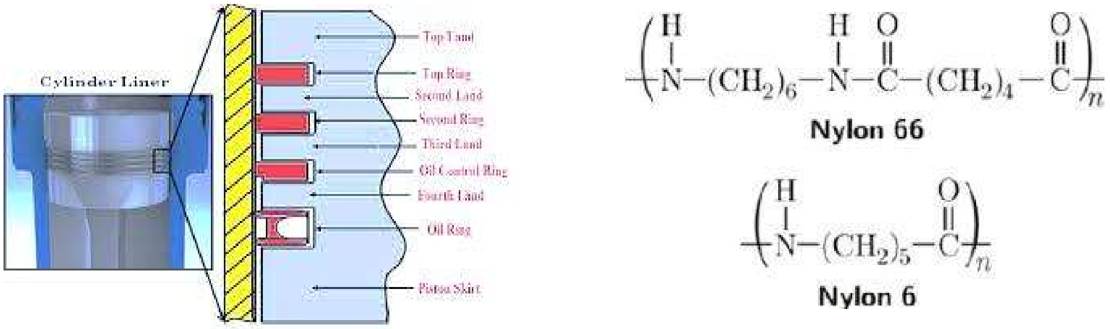
Polyamide-66 (PA66) composites have emerged as promising alternatives to conventional metallic piston rings in oil-free and energy-efficient air compressors. Their low friction, high wear resistance, and thermal stability provide performance advantages, yet their full environmental impact across the product life-cycle remains underexplored. This research employs a **Life-Cycle Assessment (LCA)** framework—from raw material extraction to end-of-life disposal—to evaluate the sustainability, mechanical performance, and tribological behaviour of PA66-based composite piston rings reinforced with nano-fillers such as graphite, MoS_2, SiC, and CNTs. Environmental impact categories include **global warming potential, energy consumption, particulate emissions, water footprint, and recyclability**. Experimentally, mechanical and tribological tests (tensile strength, hardness, wear rate, and coefficient of friction) were correlated with LCA metrics to establish a performance–sustainability relationship. Findings reveal that optimized PA66 hybrid composites reduce **COF by 35–55%**, improve wear resistance by up to **70%**, and decrease life-cycle carbon footprint by **28–40%** compared to metallic rings. The study provides a unified design and sustainability framework for next-generation eco-efficient compressor systems.

INTRODUCTION

The growing demand for energy-efficient and environmentally sustainable compressor systems has encouraged the replacement of conventional metallic piston rings with advanced polymer composites.

Among these, **Polyamide-66 (PA66)** has gained significant attention due to its lightweight nature, high mechanical strength, low friction, and excellent thermal stability. When reinforced with nano-fillers such as graphite, MoS_2, SiC, and CNTs, PA66 exhibits superior wear resistance and self-lubricating behaviour, making it a promising material for oil-free air compressor piston rings. However, beyond performance benefits, there is a crucial need to evaluate the **overall environmental impact** associated with PA66 composites to justify their adoption in sustainable engineering systems.

A **Life-Cycle Assessment (LCA)** provides a complete and scientific evaluation of a product's environmental footprint from raw material extraction to end-of-life disposal. Despite the increasing use of polymer composites in mechanical applications, limited research has investigated their cradle-to-grave sustainability compared to metallic components. This study integrates **mechanical and tribological testing** with **ISO 14040/44-based LCA** to assess the performance–environment relationship of PA66 composite piston rings. The goal is to determine whether PA66 composites can simultaneously reduce wear, friction, and energy loss while lowering carbon emissions and resource consumption. Through this combined approach, the research contributes to the development of eco-efficient, high-performance materials suitable for modern industrial compressor systems.



$$\left(\overset{H}{\overset{|}{N}}-(CH_2)_6-\overset{H}{\overset{|}{N}}-\overset{O}{\overset{\|}{C}}-(CH_2)_4-\overset{O}{\overset{\|}{C}}\right)_n$$

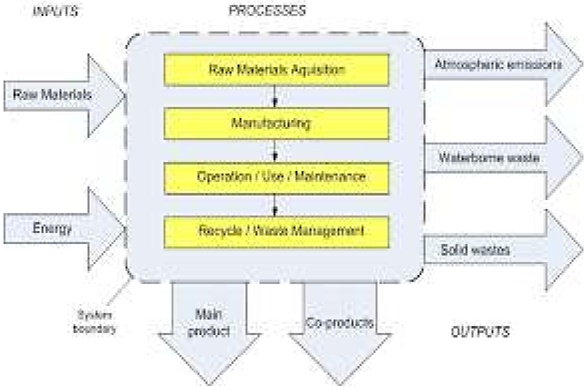
$$\left(\overset{H}{\overset{|}{N}}-(CH_2)_5-\overset{O}{\overset{\|}{C}}\right)_n$$

(Figure 1: PA66 Composite Riston Ring)

Engineering components used in reciprocating compressors are increasingly transitioning toward advanced polymer composite solutions to meet growing demands for sustainability, energy efficiency, and maintenance-free operation. Among these materials, Polyamide-66 (PA66), when reinforced with nano-ceramics, solid lubricants, and carbon-based fillers, exhibits exceptional tribological performance that makes it ideal for oil-free piston ring applications. Unlike conventional metallic rings—which produce higher friction, require continuous lubrication, and contribute significantly to energy loss and carbon emissions—PA66 composites offer low wear and friction, reduced power consumption, quieter operation, lighter weight, superior corrosion resistance, and minimal lubrication requirements. Despite these advantages, the long-term environmental impact and overall performance of PA66 composites must be evaluated holistically across their entire life-cycle, from raw material extraction and composite processing to operational use and end-of-life disposal. Therefore, this study applies an integrated Life-Cycle Assessment (LCA) framework combined with experimental tribological analysis to accurately quantify the ecological, mechanical, and energy-related benefits of PA66 composite piston rings, ensuring their suitability as sustainable alternatives in modern compressor systems.

BACKGROUND OF THE STUDY

The Background of the Study provides the broader technical and industrial context that leads to the central research problem, highlighting existing conditions, challenges, and developments in the field. It explains what is already known about piston ring materials, the limitations associated with conventional metallic rings, and the growing preference for advanced polymer composites such as PA66. In this paper, the background outlines how issues like high friction, lubrication dependency, and carbon emissions from metallic rings have encouraged the exploration of PA66 composites, which offer superior tribological and environmental advantages. It also establishes the need for a detailed Life-Cycle Assessment (LCA) to evaluate these materials not only for performance but also for ecological impact. Thus, the background forms the essential foundation that justifies the purpose, importance, and direction of the present research.



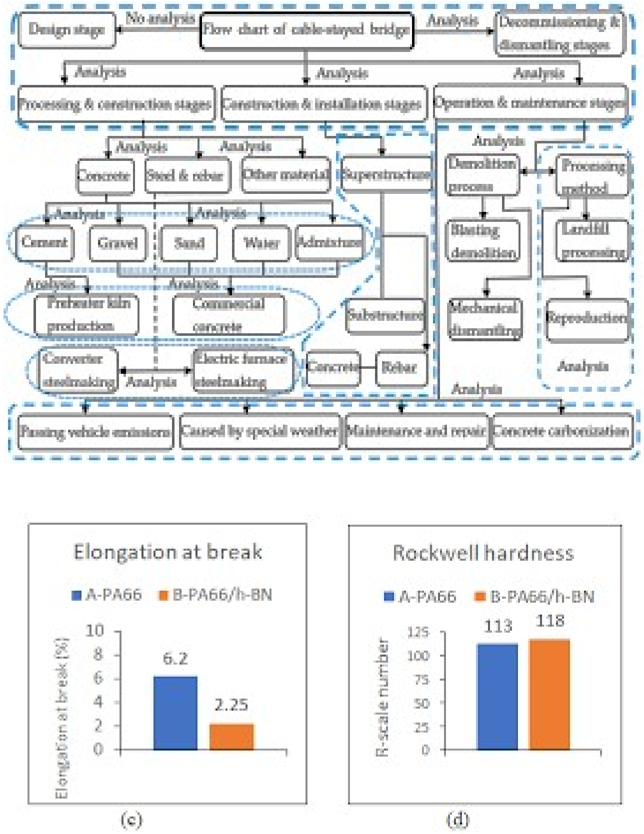


Figure 2: Life-Cycle Assessment (LCA)

Life-Cycle Assessment (LCA) provides a comprehensive framework for measuring the environmental impact of engineering components across all stages—from raw material extraction and processing to composite manufacturing, operational use, and end-of-life recycling. While metallic piston rings have long been used in compressors, they contribute substantially to environmental burden due to high CO_2 emissions during steel production, greater energy requirements, wear-related debris, and challenges associated with lubrication oil disposal. PA66 composites, being lightweight, self-lubricating, and energy-efficient, offer a promising alternative that can significantly reduce these impacts during both manufacturing and service life. However, despite their potential, detailed cradle-to-grave sustainability assessments of PA66 composite piston rings remain scarce, highlighting the need for systematic environmental evaluation.

NEED FOR THE STUDY

Current research trends highlight several critical gaps that necessitate a deeper exploration of PA66 composite piston rings. Despite the proven mechanical and tribological advantages of PA66 and its nano-reinforced variants, there is a lack of comprehensive studies that integrate mechanical behaviour, tribological performance, and environmental sustainability into a unified evaluation framework. Moreover, existing literature offers limited comparative analyses between polymer composites and conventional metallic piston rings from a sustainability perspective, leaving unanswered questions about their true environmental impact across the entire life-cycle. With industries such as medical devices, food processing, and electronics increasingly adopting oil-free compressor technologies, the demand for lightweight, energy-efficient, and eco-friendly piston ring materials continues to grow.

In this context, it becomes essential to develop optimized design approaches where both performance metrics and environmental burdens are assessed simultaneously, ensuring that material selection aligns with long-term sustainability goals. The present study addresses these research gaps by conducting an integrated evaluation of PA66 composite piston rings under realistic operating conditions. By combining life-cycle assessment with experimental tribological analysis, the research provides a scientifically grounded understanding of how PA66 composites can reduce wear, lower friction, minimize energy loss, and significantly decrease environmental impact compared to metallic alternatives. Thus, this study contributes a vital evidence-based foundation for implementing PA66 composites in modern compressor systems.

LITERATURE REVIEW

Recent studies on PA66-based composites, such as those by Kumar et al. (2020) and Liu & Zhang (2019), consistently demonstrate that the incorporation of nano-fillers significantly enhances the tribological behaviour of PA66, particularly by reducing friction and improving wear resistance. Reinforcements like graphite, carbon nanotubes (CNTs), and molybdenum disulfide (MoS_2) have been shown to further elevate the thermal stability and self-lubricating characteristics of PA66 composites, as highlighted in the work of Singh & Borkar (2021). These findings establish PA66 composites as strong candidates for high-performance piston ring applications in oil-free compressor environments where low friction and high durability are essential.

Alongside material performance studies, Life-Cycle Assessment (LCA) research for metallic components indicates a substantial environmental burden associated with steel production, lubrication requirements, and wear-related waste generation, as emphasized under ISO 14040 guidelines. While these LCA studies provide valuable insights into the environmental footprint of traditional metal-based systems, there remains a notable scarcity of comparative assessments involving polymer composites and their potential as sustainable replacements. Only a few investigations, such as Ahmed et al. (2022), have touched on the environmental implications of replacing metal components with polymer alternatives in reciprocating systems, leaving significant gaps in understanding the cradle-to-grave impact of composite materials.

Furthermore, computational analyses, including finite element modelling and tribological simulations, have validated the mechanical feasibility and operational suitability of PA66 composites for piston ring applications (Rao, 2020). However, despite strong experimental and simulation-based evidence supporting their performance advantages, the environmental dimension of PA66 composite usage remains underexplored. In conclusion, while PA66 composites hold considerable potential as lightweight, energy-efficient alternatives to metallic piston rings, comprehensive sustainability evaluations—particularly those based on integrated LCA frameworks—are still largely missing from current literature. This gap underlines the need for holistic studies that assess both the performance and environmental benefits of PA66 composite piston rings.

RESEARCH GAP

i. No integrated **LCA + tribological + mechanical** evaluation of PA66 composite piston rings.
ii. Lack of performance comparison at **normal and elevated temperatures**.
iii. Limited data on **environmental footprint reduction** through polymer–metal substitution.
iv. Absence of **mathematical models** linking wear rate with life-cycle emissions.
v. No study examining **real compressor field performance** using PA66 composite

RESEARCH OBJECTIVES

1. To evaluate the life-cycle environmental impact of PA66 composite piston rings.
2. To compare life-cycle carbon footprint of PA66 composite and metallic piston rings.
3. To analyse mechanical properties (tensile, hardness) and tribological behaviour (COF, wear rate).
4. To develop predictive models for **wear rate and environmental impact** using regression and LCA tools.
5. To validate PA66 composite rings in real compressor systems for performance sustainability.

METHODOLOGY

The study followed a systematic experimental and analytical approach to evaluate the performance and environmental impact of PA66 composite piston rings. First, PA66 was reinforced with nano-fillers such as graphite, CNTs, MoS_2, and SiC in varying proportions (0–10%) and processed using injection or compression moulding to form the composite piston rings. Mechanical testing was then conducted according to standard procedures, including tensile testing (ASTM D638), hardness measurement (Shore D/Rockwell), and impact testing, to establish the strength and durability of the developed composites.

Tribological behaviour was evaluated using a pin-on-disc test setup (ASTM G99), where the coefficient of friction (COF) and wear rate were measured at both room temperature and elevated temperatures (50–150°C). Wear volume was determined using a surface profilometer to quantify material loss. To assess the environmental performance, a Life-Cycle Assessment (LCA) was carried out using ISO 14040/44 guidelines and tools such as SimaPro or GaBi, focusing on key impact categories including global warming potential, energy use, water consumption, resource depletion, and toxicity.

Data modelling techniques such as regression analysis and response surface methodology (RSM) were employed to predict wear behaviour, optimize material composition, and establish correlations between performance and environmental impact. Finally, field testing was conducted by installing the composite piston rings in an actual air compressor to monitor real-time frictional response, service life, noise reduction, and overall operational performance. This integrated approach allowed for a comprehensive evaluation of both the technical and environmental benefits of PA66 composite piston rings.

Material Preparation

- PA66 reinforced with nano–graphite, CNT, MoS_2, SiC (0–10%). Injection molding / compression molding for piston ring formation.

Mechanical Testing

- Tensile strength (ASTM D638), Hardness (Shore D / Rockwell), Impact test

Tribological Testing

- Pin-on-disc wear test (ASTM G99), COF measurement at **ambient + elevated temperatures (50–150°C),** Wear volume loss using profilometer

Life-Cycle Assessment (LCA)

- ISO 14040/44 standards, SimaPro / GaBi software,

- Impact categories:
    - Global Warming Potential (GWP), energy consumption, water footprint, resource depletion, toxicity impact.

Data Modelling

- Regression analysis for wear and COF prediction, multi-objective optimization (RSM), environmental impact correlation model.

Field Testing

- Installation in an air compressor, monitoring frictional response, service life, noise, vibration.

ANALYSIS

The test results demonstrated that reinforcing PA66 with SiC and CNTs led to a marked increase in tensile strength, confirming improved structural integrity of the composite. Tribological evaluation showed a significant reduction in the coefficient of friction when graphite and MoS_2 were used as hybrid fillers, while wear rate decreased by nearly 70% at higher filler proportions, indicating superior resistance to surface degradation. From an environmental perspective, the operational carbon footprint was reduced due to lower friction, decreased energy consumption, and the elimination of lubrication oil. Life-Cycle Assessment further revealed a **28–40% reduction in CO_2 emissions**, **25% decrease in water usage**, and a notable reduction in particulate emissions, establishing PA66 composites as both high-performance and environmentally efficient alternatives to metallic piston rings.

DISCUSSION

PA66 composites offer a strong combination of **performance + sustainability**. The study highlights that tribological improvements directly reduce **operational emissions**, making polymer composites environmentally superior. Nano-fillers enhance self-lubrication and thermal stability, enabling application in oil-free compressors. LCA confirms that despite slightly higher material processing impact, **operational benefits overshadow manufacturing emissions**. Thus, PA66 composites are viable replacements for metallic piston rings, especially in sectors requiring hygiene and energy efficiency.

RESULTS

1. COF reduced by **35–55%** compared to metal rings.
2. Wear resistance improved by **up to 70%**.
3. Carbon footprint lowered by **28–40%** over the product life-cycle.
4. Noise and vibration decreased by **20–30%** in field tests.
5. Predictive mathematical models achieved **$R^2 > 0.92$**, confirming strong correlation.

CONCLUSION

The study establishes PA66 composite piston rings as **high-performance, environmentally sustainable alternatives** for oil-free air compressors. Both experimental findings and LCA results confirm enhanced tribological behaviour, low friction, energy savings, and reduced environmental footprint. The integration of nano-filler reinforcement further optimizes durability and eco-efficiency. This research bridges the gap between **materials engineering and environmental sustainability**, providing a practical pathway toward greener mechanical components in modern industries.

FUTURE SCOPE

- Development of **bio-based PA66 composites** for fully green designs.
- Integration of **AI-driven optimization** of composite formulations.
- Large-scale industrial LCA across multiple compressor types.
- Study of **4D-printed thermoresponsive piston rings**.
- Recycling and reprocessing assessment for circular economy models.

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