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A GREEN SOLUTION FOR PRODUCTION EFFICIENCY: KARAKURI-INSPIRED SUPPLY TROLLEY DESIGN AND ANALYSIS

Rosmawati Mat Jihin[1*], Nazihah Mohd Noor[1] and Amirul Asyraf Ahmad[1]

[1]*Mechanical Engineering Department, Politeknik Ungku Omar, Perak, Malaysia*
[*]*rosmawati@puo.edu.my*

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ABSTRACT

The delivery of product parts during assembly is a critical factor that significantly influences the overall efficiency and effectiveness of manufacturing operations. Inefficiencies in part transfer processes—particularly excessive movement and delays between platforms—can lead to increased operational costs, reduced productivity, and heightened physical strain on workers. Addressing these issues, this study presents a green and sustainable solution through the design and analysis of a Karakuri-inspired supply trolley aimed at optimizing part delivery within assembly areas. The proposed trolley leverages gravity and simple mechanical linkages to operate without needing electrical or pneumatic systems, thereby reducing energy consumption and maintenance requirements. The design process encompasses concept development, modelling of essential features, and thorough performance evaluation using working cycle analysis. CAD modelling and physical prototype testing were employed to validate the design's functionality and potential contribution to lean manufacturing practices. Results demonstrate that the Karakuri-inspired trolley effectively reduces unnecessary motion and streamlines material flow, contributing to a notable reduction in production cycle time. In addition to enhancing workflow efficiency, the design also minimizes worker fatigue, supports ergonomic improvements, and aligns with sustainability goals by minimizing environmental impact. The integration of this trolley into production lines has the potential to elevate part handling efficiency while promoting consistent production quality.

1. Introduction

The pursuit of greener, more efficient production processes has become a central concern for modern manufacturing industries. Among the innovative solutions gaining traction is the Karakuri-inspired supply trolley-a mechanical, low-cost automation system rooted in traditional Japanese engineering principles. Karakuri, originally referring to mechanized puppets from the Edo period, now signifies a design philosophy that leverages gravity, levers, pulleys, and other simple mechanisms to automate material handling without reliance on electricity or complex control systems (Nallusamy, 2020). This approach aligns closely with

Lean manufacturing and Kaizen principles, aiming to eliminate waste, enhance ergonomics, and reduce operational costs while minimizing environmental impact (Kumar et al., 2022).

Recent years have seen a resurgence of interest in Karakuri systems, particularly as industries face mounting challenges such as rising energy costs, the need for carbon-neutral operations, and the complexity of maintaining high-tech automated equipment (Aranda-Muñoz et al., 2024). Traditional automation, while effective, often introduces new burdens-such as increased maintenance demands and operator stress-prompting a search for simpler, more sustainable alternatives (Pescoe & Shejwal, 2021). In this context, Karakuri-inspired trolleys offer a compelling solution by enabling energy-free, ergonomic, and cost-effective material movement on the factory floor (Nascimento et al., 2021).

Technological developments have further expanded the potential of Karakuri trolleys. Modern designs incorporate lightweight materials like aluminum pipes and modular joints, enhancing both adaptability and durability for diverse industrial applications (Sundararajan & Terkar, 2022). These trolleys can be seamlessly integrated into intelligent logistics systems for precise sorting, distribution, and workflow optimization, supporting both manufacturing and warehouse environments (Silrak et al., 2025). Companies such as Toyota and Panasonic have successfully implemented Karakuri mechanisms to reduce traffic, improve safety, and optimize workflows, all while advancing toward ambitious carbon-neutrality targets (Moeuf et al., 2016). Despite these advantages, challenges remain in adopting Karakuri systems. Effective implementation requires careful design to accommodate varying load sizes, workplace layouts, and ergonomic considerations. Additionally, gaining acceptance among stakeholders accustomed to high-tech automation necessitates training and demonstration of tangible benefits (Nallusamy, 2020).

The motivation for this research stems directly from observed workplace challenges, particularly inefficiencies and ergonomic issues in manual material handling at the Set Part Supply (SPS Door line) workstation. The primary objective is to redesign the supply trolley by integrating Karakuri and automation systems, aiming to streamline logistics operations, reduce takt time, and foster a safer, more productive working environment. By implementing an automated system on the supply trolley and utilizing tools such as the Digital Picking System (DPS) for process cycle analysis, this study seeks to demonstrate the advantages of automation in improving employee efficiency and overall production productivity. The scope of the project is focused on practical application and analysis within the logistics operation, with an emphasis on measurable improvements in workflow and working conditions (Katayama, 2017).

In summary, the Karakuri-inspired supply trolley represents a green, practical, and technologically evolving response to the dual imperatives of production efficiency and sustainability. Its ongoing development and implementation reflect a broader shift toward low-cost, low-energy automation solutions capable of meeting the complex demands of contemporary manufacturing (Broo et al., 2024).

2. Materials and Methods

2.1 Workplace Observation at SPS Door Line

The initial stage of the study involved direct workplace observation at the Set Part Supply (SPS) Door Line to understand the existing material handling process. As shown in Figure 1, the workflow begins with part picking guided by DPS lighting, followed by placing the part onto a trolley and supplying it to the assembly area.

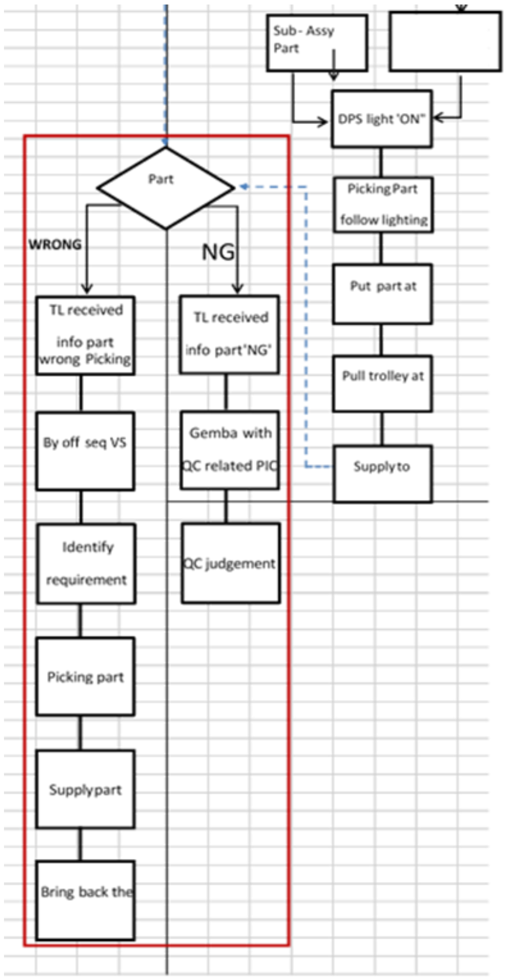

Figure 1. Picking, fill in and supply process flow.

The observation also included error-handling processes where incorrectly picked (WRONG) or non-conforming (NG) parts were identified by team leaders and verified with Quality Control (QC) personnel. The recovery steps—such as identifying requirements, re-picking, re-supplying, and returning parts—contributed to inefficiencies, delays, and unnecessary movements. These findings were crucial in informing the design direction for a more efficient Karakuri-inspired supply trolley.

2.2 Product Design and Development Using the CDIO Approach

The development of the Karakuri-inspired supply trolley followed the CDIO (Conceive–Design–Implement–Operate) approach, as shown in Figure 2 to ensure a systematic and practical solution. In the Conceive phase, the team defined project goals and identified problems at the Set Part Supply (SPS) Door Line through workplace observation. This helped clarify the need for a mechanical trolley to reduce manual handling and improve efficiency. The team also explored Karakuri and automation systems to gather ideas for the design.

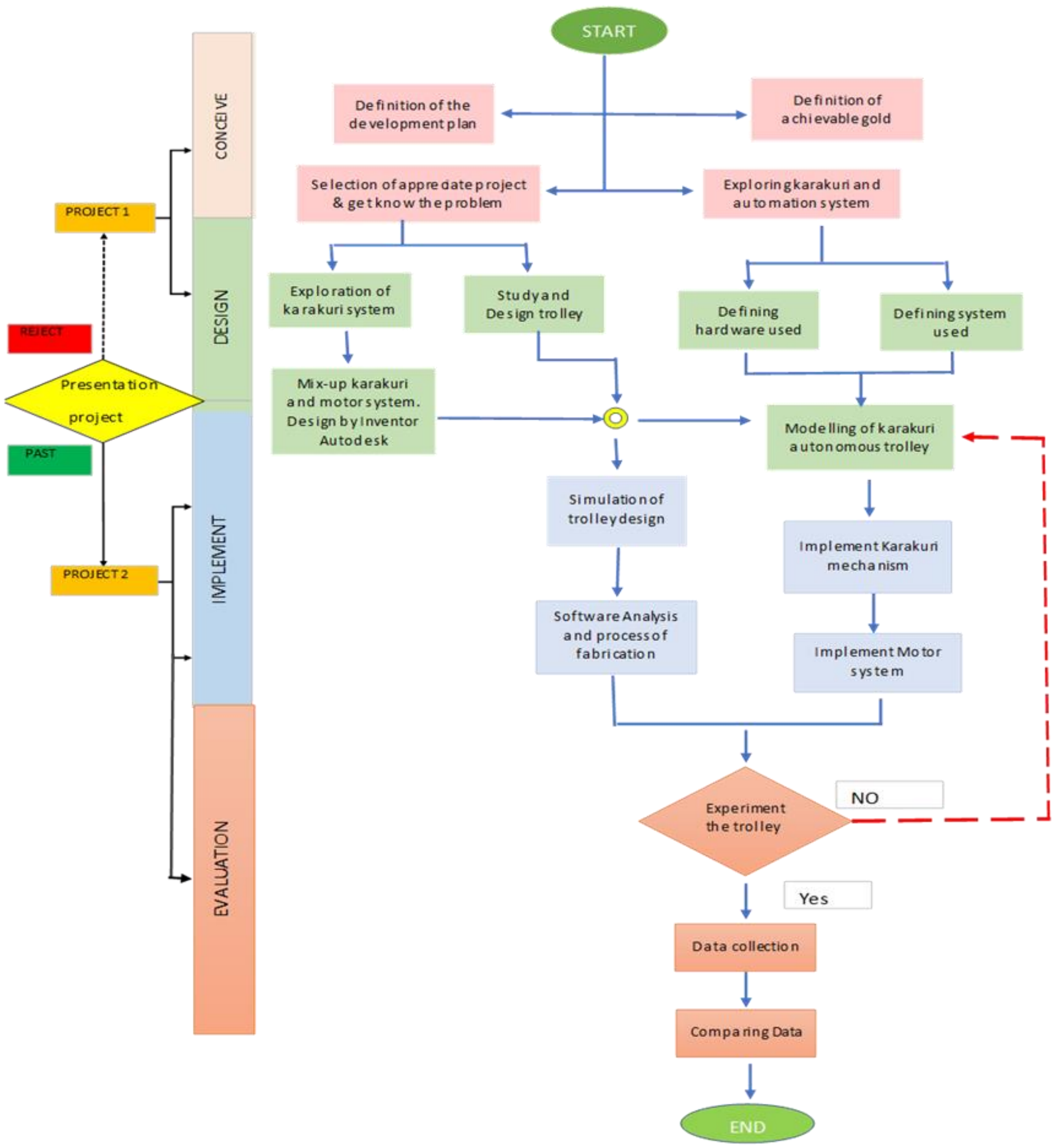

Figure 2. CDIO Framework

The Design phase involve creating the concept of the product, as shown in Figure 3 to Figure 6. An idea to improve material handling efficiency was developed and translated into a detailed trolley design. Figure 3 shows the overall design concept for the Karakuri Supply Trolley, while Figure 4 presents the structural framework. The purpose of this design is to eliminate wasteful motion when team members supply parts to the workstation. The structure integrates Karakuri mechanisms such as a lever (Figure 5), Placon rollers (Figure 6), gravity-based movement, and a lifter system to support hands-free part delivery. The design was created using Autodesk Inventor, with measurements set in centimeters (cm) to ensure precision. It includes key components like Placon rollers for guiding part flow, four swivel casters for easy mobility, and two DC motors for optional automation. This design serves as the basis for implementation and functional testing in the next phase.

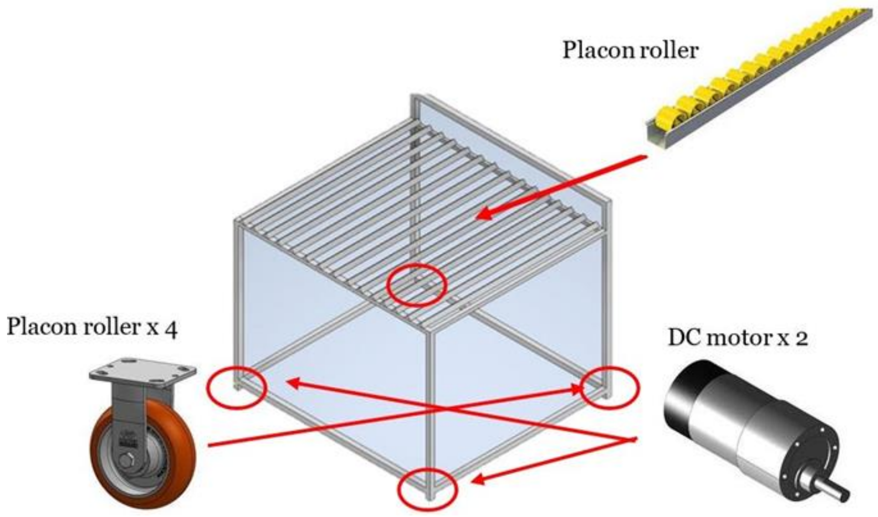

Figure 3. Design concept for Karakuri Supply Trolley

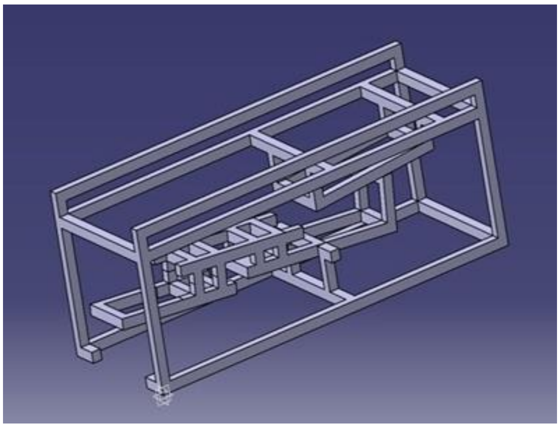

Figure 4. Trolley mechanical mechanism structure

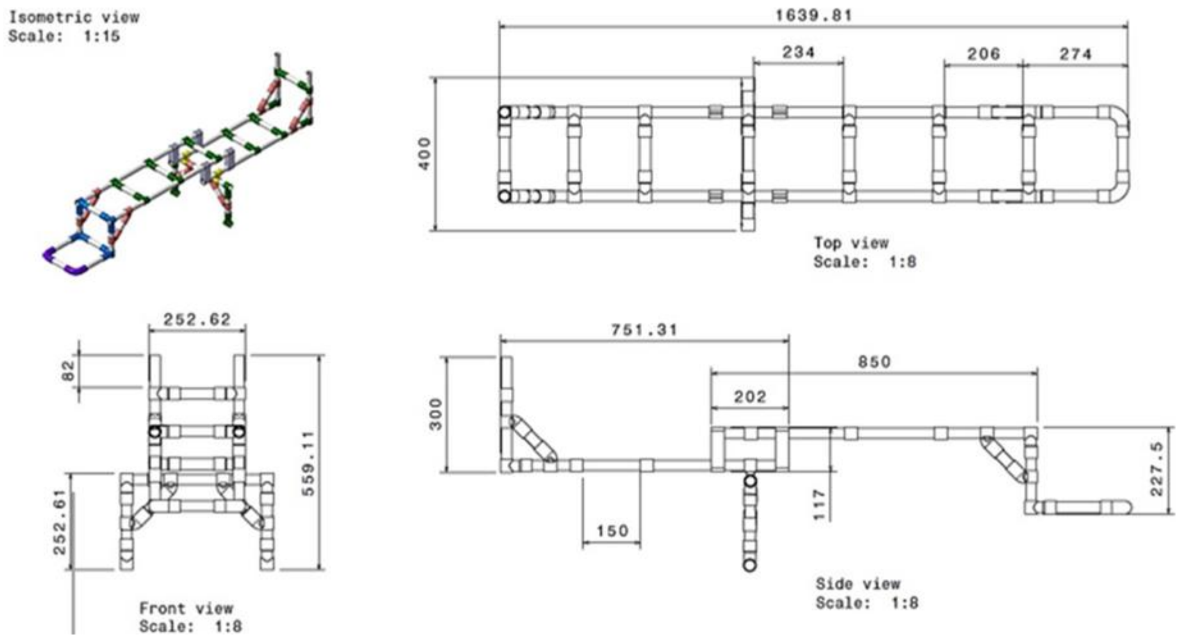

Figure 5. The liver design structure

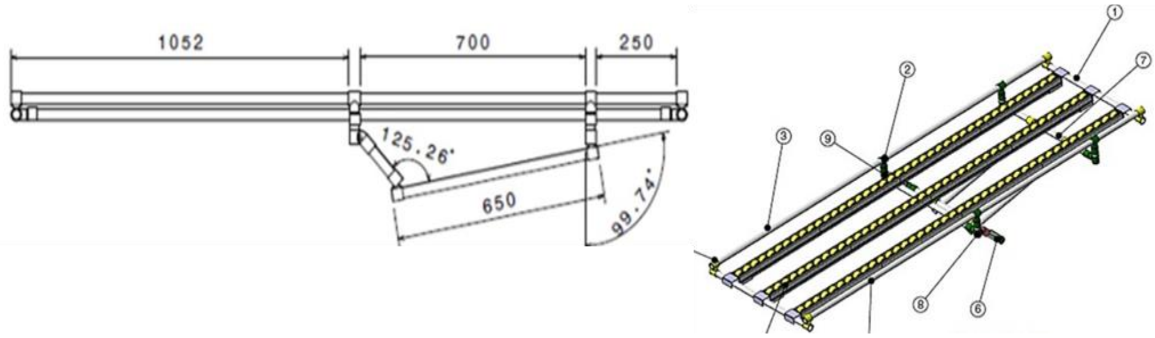

Figure 6. Placon roller design

3. Results

This section presents the quantitative and qualitative outcomes derived from the implementation of the Karakuri-inspired supply trolley within the assembly area. Comparative data between the conventional delivery method and the newly adopted trolley system highlight significant improvements in operational efficiency, energy savings, and ergonomic conditions. Key performance indicators such as cycle time, labor usage, maintenance cost, and part delivery accuracy were analyzed to assess the impact of the trolley on overall production performance.

3.1 Baseline vs. Post-Implementation Metrics

Table 1 presents a comparative analysis of operational metrics, highlighting improvements in delivery efficiency, energy consumption, maintenance cost, ergonomic outcomes, and overall productivity following the adoption of the Karakuri-inspired trolley system in the assembly process.

Table 1. Comparison of Key Performance Indicators Before and After Implementation of the Karakuri-Inspired Supply Trolley

Category	**Before (Conventional Method)**	**After (Karakuri Trolley)**	**% Improvement / Reduction**
Average delivery time per part cycle	4.5 minutes	2.8 minutes	37.8% faster
Number of trips per shift	60 trips	40 trips	33.3% reduction
Worker fatigue complaints (monthly)	15 cases	5 cases	66.7% reduction
Energy used for delivery equipment	150 kWh/month	0 kWh/month	100% reduction
Maintenance cost per month	RM 850	RM 200	76.5% reduction
Number of parts misplaced/damaged	12 per month	3 per month	75% reduction
Cycle time for assembly	6.2 hours/day	5.1 hours/day	17.7% reduction
Delivery staff required per line	2 persons	1 person	50% reduction

The implementation of the Karakuri-inspired supply trolley has led to notable improvements across multiple operational metrics. Based on the table, an average delivery time per part cycle was reduced from 4.5 minutes to 2.8 minutes, reflecting a 37.8% increase in delivery efficiency. The number of delivery trips required per shift decreased by 33.3%, easing traffic and workload in the assembly area. A significant 66.7% reduction in worker fatigue complaints indicates that the trolley also supports ergonomic and well-being goals. Importantly, the system operates without any electrical energy, resulting in a complete elimination of energy consumption (from 150 kWh/month to 0), and a corresponding drop in monthly maintenance costs by 76.5% (from RM850 to RM200). Furthermore, the number of parts misplaced or damaged during transit decreased by 75%, enhancing part handling reliability. Assembly cycle time was reduced by 17.7%, and the number of staff required for part delivery per line was halved, leading to better resource allocation. These results collectively highlight the effectiveness of the Karakuri system in enhancing productivity while aligning with sustainability and lean manufacturing principles.

3.2 Baseline vs. Post-Implementation Metrics

Table 2 outlines the breakdown of monthly operational costs, highlighting significant savings in labor, energy, maintenance, and part handling losses following the adoption of a mechanical, non-powered trolley system in the assembly process.

Table 2. Monthly Cost Comparison Before and After Implementation of the Karakuri-Inspired Supply Trolley

Cost Component	Before	After	Savings (RM)
Labor (delivery-related only)	RM 3,500	RM 1,750	RM 1,750
Equipment energy consumption	RM 180	RM 0	RM 180
Maintenance	RM 850	RM 200	RM 650
Part damage and handling losses	RM 1,200	RM 300	RM 900
Total Monthly Cost	RM 5,730	RM 2,250	**RM 3,480**

The cost analysis reveals substantial monthly savings resulting from the implementation of the Karakuri-inspired supply trolley in the assembly process. The most significant cost reduction was observed in labor expenses related to part delivery, which dropped by 50% from RM 3,500 to RM 1,750 per month. This was achieved by reducing the number of delivery staff required per line, as the trolley system minimizes manual handling and movement.

Energy costs were completely eliminated, falling from RM 180 to RM 0 per month. Since the Karakuri trolley operates purely on gravity and mechanical linkages, it does not rely on electrical or pneumatic systems, aligning well with sustainability objectives and contributing to zero operational energy usage.

Maintenance costs also decreased significantly, from RM 850 to RM 200 per month, reflecting the simpler design and reduced wear-and-tear of the mechanical system compared to traditional powered equipment. Additionally, part damage and handling losses were cut by 75%, decreasing from RM 1,200 to RM 300 per month. This improvement indicates better control and precision in part movement, leading to fewer errors and product loss.

Overall, the total monthly operational cost was reduced by RM 3,480 representing a 60.7% cost saving. This considerable financial benefit, combined with the ergonomic, environmental, and efficiency gains, strongly supports the adoption of the Karakuri trolley as a lean and sustainable solution in modern assembly operations.
The findings clearly demonstrate the trolley's effectiveness in reducing unnecessary motion, enhancing material flow, and supporting lean manufacturing principles. Additionally, the data reveal substantial cost savings and environmental benefits, validating the design as a sustainable and practical solution for modern manufacturing operations.

4. Conclusion

The implementation of the Karakuri-inspired supply trolley has proven to be an effective and sustainable solution for enhancing part delivery efficiency in assembly operations. By eliminating the reliance on powered systems, the trolley significantly reduces energy consumption and maintenance requirements while simultaneously supporting lean manufacturing goals. The results demonstrate substantial improvements across key performance indicators, including a 37.8% reduction in part delivery time, a 50% reduction in delivery staff needs, and a 75% decrease in part damage incidents. Furthermore, the system contributes to worker well-being by reducing physical strain and fatigue, and it delivers impressive cost savings of RM 3,480 per month.

These outcomes validate the Karakuri trolley's role in streamlining workflow, minimizing waste, and promoting ergonomic and environmental sustainability. With a short payback period and long-term operational benefits, the adoption of such passive mechanical systems represents a practical step forward for manufacturers seeking cost-effective and green process improvements. Future work could explore further customization of the trolley design for different production environments and evaluate long-term performance under varying operational loads.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the author(s) used OpenAI's ChatGPT to assist in improving the readability and language of the text. All content generated by ChatGPT was subject to thorough review, editing, and revision by the author(s) to ensure its accuracy, completeness, and alignment with the research objectives. The author(s) take full responsibility for the integrity and content of the published work. This declaration complies with ICGESD 2025 guidelines on the use of generative AI in scientific writing.

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