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DMAIC-Integrated ISO 14001, LCA and Green Six Sigma for Hazardous Waste in Peruvian University Laboratories

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Abstract

Industrial hazardous-waste regulations seldom fit academic laboratories, where small batches, diverse chemicals, and rotating users prevail; prior studies apply ISO 14001, LCA, Lean and Six Sigma mostly in industry. This work addresses urgent compliance and safety gaps in a Peruvian university's laboratories. We integrate ISO 14001, LCA principles, Green Lean, and Green Six Sigma within a DMAIC framework, using E-VSM, cradle-to-grave tracking, digitalized forms, and targeted training. Audited results show notable improvements across key indicators: compliance increased from 22% to 61% in Industrial Engineering and from 18% to 78% in Civil Engineering. Storage time beyond the legal limit was significantly reduced, and both document traceability and training coverage improved considerably, traceability from 45% to 75%, and training from 53% and 10% to over 90%. Academically, the study adapts industrial-quality tools to high-variability academic settings; socioeconomically, it reduces risk and strengthens institutional governance. We invite researchers to test the model across faculties and quantify environmental impacts with full LCA.

Keywords
Sustainability, Compliance, Traceability, Hazardous Waste Management, Green Six Sigma.

1. Introduction
Hazardous waste management has historically focused on large-scale industrial sectors, leaving aside other relevant generators such as higher education institutions. Universities, particularly those engaged in scientific and technological activities, handle a wide variety of chemicals in academic and research laboratories. Unlike industry, where processes are standardized and tightly controlled, the academic context is characterized by high variability in waste generation and management practices. This situation has created gaps in the implementation of integrated management systems that ensure safe, efficient, and sustainable handling of hazardous materials (Gutiérrez & Silva, 2020; Jafari et al., 2021).

The absence of management models adapted to the university context increases operational, environmental, regulatory, and reputational risks. As noted by Fernández et al. (2021), inadequate handling of hazardous waste can lead to water and air quality deterioration, health risks, and regulatory sanctions. This challenge is particularly critical in institutions dedicated to training professionals, where mismanagement not only compromises safety but also undermines the environmental and ethical values being taught. Despite the availability of frameworks such as ISO

14001, their implementation in Peruvian universities remains limited. Therefore, it is essential to establish an environmentally sound management system that addresses the entire life cycle of hazardous waste and its technical, social, and economic implications (Gutiérrez & Silva, 2020; Fernández et al., 2021).

In response to these challenges, this study proposes an integrated improvement model for hazardous waste management in universities, structured under a process-based and quality-oriented approach. The model combines ISO 14001, Green Lean, and Green Six Sigma within the DMAIC cycle (Define, Measure, Analyze, Improve, and Control). Using tools such as cradle-to-grave analysis, Environmental Value Stream Mapping (E-VSM), and root cause diagrams, the model aims not only to ensure regulatory compliance but also to optimize processes, reduce inefficiencies, and foster a culture of continuous improvement (Jafari et al., 2021; Fernández et al., 2021).

Despite the widespread evidence of ISO 14001, LCA, Green Lean, and Green Six Sigma in industrial settings, their transfer to university laboratories remains underreported and largely fragmented. High variability in waste streams, small-scale experiments, and frequent user rotation limit the effectiveness of industrially oriented regulations and tools, leaving compliance and process control unresolved in academic environments (Gutiérrez & Silva, 2020; Fernández et al., 2021; Jafari et al., 2021; Martínez & López, 2022).

Accordingly, this study addresses the following problem: how can university laboratories achieve sustained regulatory compliance and process stability under high variability in hazardous waste generation and handling? The research aims to design and implement an integrated, quality-based model adapted to the academic context of engineering laboratories in a Peruvian university.

The novelty of this work lies in integrating ISO 14001, LCA principles, Green Lean, and Green Six Sigma within a single DMAIC framework and operationalizing it through E-VSM, cradle-to-grave tracking, and digitalized forms. Unlike prior studies that emphasize isolated frameworks, this model delivers a coherent, auditable pathway tailored to academic laboratories characterized by high variability (Finkbeiner et al., 2010; Garza-Reyes et al., 2018; Cherrafi et al., 2019).

1.1 Objectives

The main objective of this research is to design and implement an integrated quality-based model for hazardous waste management in university laboratories, adapted to the academic context. The study aims to overcome the limitations of industrially oriented regulations and provide a framework that ensures both environmental compliance and process improvement.

The specific objectives are:

- To diagnose the current hazardous waste management practices in engineering laboratories, identifying deficiencies in compliance, segregation, traceability, and storage.
- To integrate ISO 14001 principles, Green Lean, and Green Six Sigma methodologies under the DMAIC cycle (Define, Measure, Analyze, Improve, Control) to redesign academic waste management processes.
- To apply tools such as cradle-to-grave analysis, Environmental Value Stream Mapping (E-VSM), and root cause analysis for evaluating and improving laboratory processes.
- To validate the proposed model by measuring key performance indicators, with a focus on regulatory compliance, and to assess its impact on training coverage, storage time, and traceability.
- To provide a replicable and scalable model that strengthens sustainability practices in higher education institutions, bridging the gap between industrial quality tools and academic realities.

2. Literature Review

The management of hazardous waste has become a pressing concern across sectors, driven by increasing regulatory demands and the need to minimize environmental and health risks. International standards and quality-based methodologies have been instrumental in guiding organizations toward compliance and continuous improvement. However, while significant progress has been achieved in industrial contexts, the application of these tools in higher education remains underexplored, revealing important gaps that this research seeks to address.

2.1 ISO 14001

The ISO 14001:2015 standard has been widely recognized as a cornerstone for environmental management systems (EMS). It provides organizations with a structured framework to ensure compliance with environmental regulations, reduce negative impacts, and implement sustainable practices. Its emphasis on continual improvement and integration with other management systems has consolidated its position as a global benchmark. Empirical evidence shows that the adoption of ISO 14001 improves environmental performance by institutionalizing standardized processes and regular audits (Redinger & Levine, 2000).

Beyond the industrial sphere, ISO 14001 has also demonstrated applicability in more complex and diverse environments, such as universities. Chin et al. (2019) and AuYong et al. (2019) highlight that its implementation strengthens traceability and operational efficiency in academic campuses, where variability in processes and waste streams is higher than in manufacturing. Furthermore, Jadhav et al. (2019) show that even small and medium-sized enterprises benefit from its adoption, significantly reducing waste generation. This evidence supports the view that ISO 14001 can also be effective in non-industrial organizations, including educational institutions that face similar challenges in hazardous waste management.

2.2 Life Cycle Assessment (LCA)

In parallel with ISO 14001, the Life Cycle Assessment (LCA) has emerged as an indispensable methodology for evaluating environmental impacts holistically. Aligned with ISO 14040 and 14044, LCA allows organizations to assess environmental impacts from the extraction of raw materials to final disposal, providing a scientific basis for decision-making. Studies such as Oguzcan et al. (2019) have demonstrated the utility of LCA in hazardous municipal waste management, identifying environmental trade-offs and avoiding unintended substitutions.

The flexibility of LCA is evident in its application to urgent contexts, such as the COVID-19 pandemic, where Nabavi et al. (2022) applied it to evaluate medical waste treatment strategies. Using methodologies like ReCiPe2016, LCA enabled the identification of environmentally preferable options during a period of crisis, highlighting its robustness as a decision-support tool. Furthermore, Singh et al. (2015) and Camacho et al. (2020) emphasize the contribution of LCA to strategic planning in environmental management systems, enabling organizations to design reduction programs supported by quantitative evidence. Likewise, Finkbeiner et al. (2010) underline its value in comparing waste management alternatives according to their environmental performance. In academic laboratories, where diverse chemical inputs are used at small scales, LCA can anticipate risks and align institutional practices with the Sustainable Development Goals (SDGs), reinforcing preventive and sustainable management.

2.3 Green Lean

At the operational level, the Green Lean approach has gained recognition as a strategic evolution of traditional lean manufacturing. By integrating environmental criteria into waste elimination practices, Green Lean promotes both operational efficiency and ecological sustainability. Several studies confirm that combining lean practices with environmental management allows for mapping and redesigning processes to minimize waste, reduce emissions, and optimize resource use (Fercoq et al., 2016; Zhu et al., 2019).

One of its most widely adopted tools, Sustainable Value Stream Mapping (Sus-VSM), expands the scope of traditional VSM by incorporating environmental indicators such as energy consumption, water usage, and solid waste generation. This provides a systemic perspective that aligns with the goals of sustainable development (Hartini et al., 2021; Garza-Reyes et al., 2018). In addition, authors like Cherrafi et al. (2019) and Kurdve et al. (2014) emphasize that Green Lean not only enhances environmental performance but also strengthens organizational outcomes by fostering a culture of continuous improvement. Importantly, Choudhary et al. (2019) validate its applicability in small and medium enterprises, proving that Green Lean is versatile enough to adapt to highly variable contexts such as universities.

2.4 Green Six Sigma

Similarly, Green Six Sigma (GSS) has positioned itself as a methodology that bridges process quality and environmental sustainability. Built upon the statistical rigor of Six Sigma and the structured DMAIC cycle, GSS addresses complex challenges with an integrated perspective. One of its most critical stages is the Analyze phase, where root causes of operational and environmental inefficiencies are identified, distinguishing symptoms from structural drivers (Venkatadri et al., 2022). This focus enables the design of sustainable solutions that prevent recurrences, thereby strengthening both environmental performance and process stability.

Rajput et al. (2022) argue that incorporating techniques such as cause-effect analysis, multivariate regression, and design of experiments (DOE) allows GSS to generate robust improvements aligned with environmental goals. Recent studies also demonstrate its role in advancing circular economy models, where resources are used more efficiently and waste generation minimized (Rajput & Singh, 2023). In heavily regulated and environmentally sensitive sectors such as chemicals and manufacturing, GSS has proven effective in reducing variability, ensuring compliance, and supporting sustainability objectives without sacrificing quality (Taner et al., 2021; Singh et al., 2023). These findings underscore its potential relevance for academic laboratories, which require both compliance and efficiency.

2.5 Research Gaps

Despite these individual advances, the literature reveals persistent limitations. While ISO 14001, LCA, Green Lean, and Green Six Sigma have been successfully applied in industrial settings, their transfer to academic contexts remains limited. Universities face unique conditions, including high variability in waste generation, the use of multiple chemical inputs in small quantities, and constant user turnover among students and researchers. Gutiérrez & Silva (2020) and Martínez & López (2022) warn that the lack of integrated methodologies in these contexts results in fragmented interventions, yielding partial rather than systemic improvements. Moreover, Fernández et al. (2021) highlight that without institutional adaptation, regulatory compliance and continuous improvement remain difficult to achieve in educational settings.

This fragmentation underscores the need for integrated models that combine the regulatory rigor of ISO standards, the systemic scope of LCA, the efficiency of Green Lean, and the statistical control of Green Six Sigma. Such models would not only enhance hazardous waste management in universities but also position them as leaders in institutional sustainability, bridging the gap between industrial methodologies and academic realities (Finkbeiner et al., 2010; Fernández et al., 2021; Gutiérrez & Silva, 2020; Martínez & López, 2022).

The observed improvements in compliance, storage time, traceability, and training align with the mechanisms reported for Lean/Green Six Sigma and ISO-driven programs in industry, yet they extend those results to academic settings by emphasizing digitalized traceability and structured training to counter user turnover (Fercoq et al., 2016; Garza-Reyes et al., 2018; Rajput et al., 2022; Taner et al., 2021).

3. Methods

This study applied a process improvement approach based on the **DMAIC cycle** (Define, Measure, Analyze, Improve, Control), which is widely recognized in Lean Six Sigma methodologies. The cycle was adapted to the academic context to integrate environmental management standards with quality tools, ensuring compliance with hazardous waste regulations and fostering continuous improvement.

Because the approach is anchored in DMAIC, E-VSM, KPI monitoring (α, β, δ, ε), and digital records, it is readily replicable across departments and scalable to other institutions. The method is also relevant for high-variability environments beyond academia—such as healthcare and research laboratories—where small batches and diverse inputs complicate compliance and process control (Figure 1).

Figure 1. Conceptual framework of the DMAIC cycle applied to hazardous waste management in academic laboratories

This conceptual diagram illustrates the integration of quality management methodologies (SIPOC, Ishikawa, E-VSM, LCA) within the DMAIC cycle to improve hazardous waste management in university laboratories. The inputs reflect the baseline situation, low compliance, excessive storage times, lack of audits, poor training, and weak traceability, while each phase of the cycle introduces tools and actions designed to address these gaps. The expected outputs include improved compliance, reduced storage times, strengthened traceability, and a culture of continuous improvement. This framework provided the structural foundation for the interventions analyzed in this study.

3.1 Define
The first phase focused on clearly identifying the problem and its scope. Key questions were formulated regarding the type, quantity, and origin of hazardous waste; storage conditions; timeframes; and associated risks. Tools such as SIPOC (Supplier–Input–Process–Output–Customer) were used to map actors, inputs, processes, and outputs of the hazardous waste management system. This mapping enabled the identification of weaknesses in segregation, documentation, and responsibility assignment. A preliminary Life Cycle Assessment (LCA) was also conducted qualitatively to visualize potential impacts from the acquisition of chemical inputs to final disposal, supporting early preventive decisions.

3.2 Measure
In the second phase, a baseline was established through the analysis of hazardous waste declaration forms, internal and external audit reports, and laboratory records. To assess performance, specific Key Performance Indicators (KPIs) were measured, including compliance rate (α), average storage time (β), training coverage (δ), and documentary traceability (ε). The main tool employed was Environmental Value Stream Mapping (E-VSM), which provided a holistic view of waste flows, storage periods, and environmental hotspots. This was complemented by a systematic review of audit results to detect recurring patterns of non-compliance and organizational weaknesses.

3.3 Analyze
The third phase sought to transform data into actionable knowledge by identifying root causes of the deficiencies detected. The Ishikawa diagram was applied to classify problems according to operational, human, material, documentary, and regulatory factors. This was combined with environmental and safety risk assessment to prioritize interventions. Criteria such as magnitude of impact, number of people exposed, urgency, feasibility, and potential for recurrence were applied to rank critical waste streams that required immediate corrective actions.

3.4 Improve
The fourth phase involved the design and implementation of targeted improvements. Corrective measures included standardization of procedures for segregation, labeling, storage, and transportation; the creation of an institutional waste generator register; and the introduction of temporary but safe storage measures. Preventive actions were also developed, such as training programs tailored to different user profiles (students, technicians, faculty), internal regulations aligned with ISO 14001 and Peruvian legislation (D.L. 1278), and pilot projects for waste minimization at source. These improvements aimed not only to correct deficiencies but also to instill a culture of preventive management and sustainability within the university.

3.5 Control
The final phase ensured the sustainability of improvements through the implementation of a monitoring and control system. This system included periodic audits, compliance reports, and a centralized digital registry of hazardous waste flows. Monitoring was structured in three axes: (i) control of waste generation and final destination, (ii) control of operational practices across storage and transportation, and (iii) monitoring of potential environmental impacts. Traceability was strengthened through cradle-to-grave tracking, requiring manifests, operator reports, and institutional databases. By linking control mechanisms with the KPIs defined in the Measure phase, the system established a feedback loop to guarantee continuous improvement and regulatory compliance.

4. Data Collection
Data for this research were collected from multiple sources within the hazardous waste management system of a Peruvian university. The primary sources were the official forms used for the generation and declaration of hazardous waste, which include information on activity, type and classification of waste, physical state, frequency of generation, quantity (kg/L), container type, and observations. These forms provided baseline data on the diversity and volume of waste streams produced by academic laboratories.

The second source of data was the hazardous waste transfer forms, which document the internal transport of hazardous waste from laboratories to the central storage facility. These forms record key information such as type of waste, storage container, quantity, and signatures of responsible parties at each stage of the transfer. Together, the generation and transfer records allowed for full tracking of hazardous waste from the point of origin to institutional storage.

In addition, complementary information was obtained from internal and external audit reports, which documented deviations, non-conformities, and opportunities for improvement in laboratory waste management practices. Records of training sessions for laboratory staff and students were also reviewed to assess the level of awareness and coverage regarding hazardous waste protocols.

To structure and interpret this information, three analytical tools were applied during the data collection process. The Environmental Value Stream Mapping (E-VSM) provided a comprehensive visualization of hazardous waste flows from generation to storage. This analysis revealed that delays and accumulation were not solely related to the volume of waste but rather to the absence of standardization, clear procedures, and sufficient technical knowledge. It also highlighted high water consumption caused by the widespread practice of diluting chemicals instead of applying proper treatment, an action that unintentionally increased environmental impact (Figure 2).

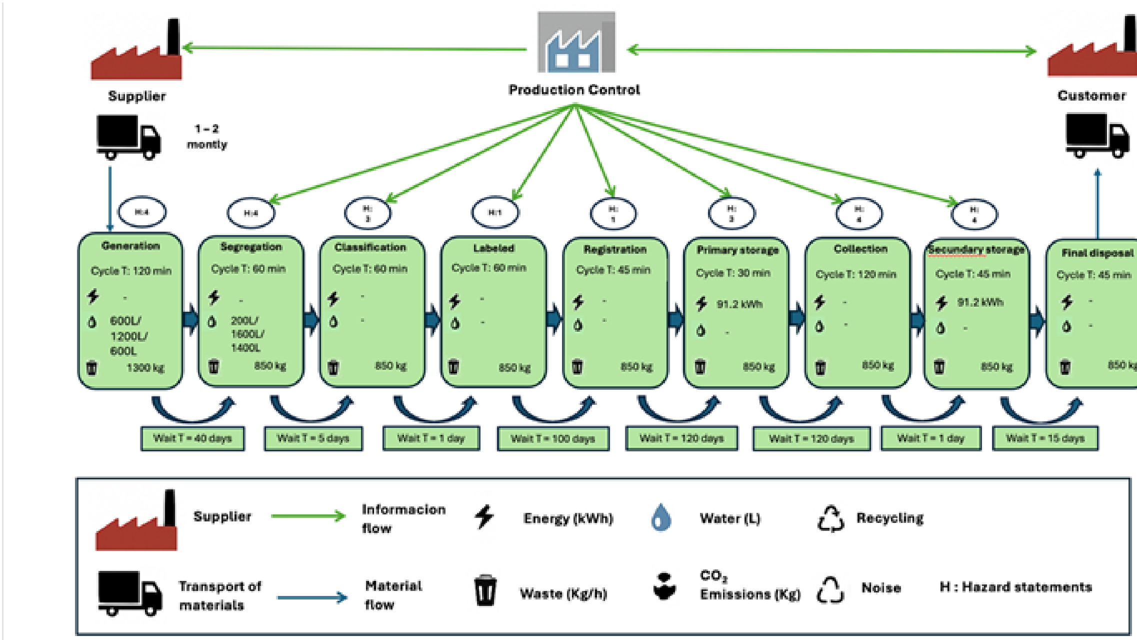

Figure 2. Environmental Value Stream Mapping (E-VSM) of hazardous waste management process in university laboratories in 2024

The Ishikawa diagram complemented these insights by categorizing the underlying causes of such practices. Recurring issues included the lack of standardized protocols, insufficient training, limited availability of certified containers, and irregular supervision. This multicausal analysis helped connect field-observed problems with their structural root causes, providing a clearer understanding of where corrective actions should be focused (Figure 3).

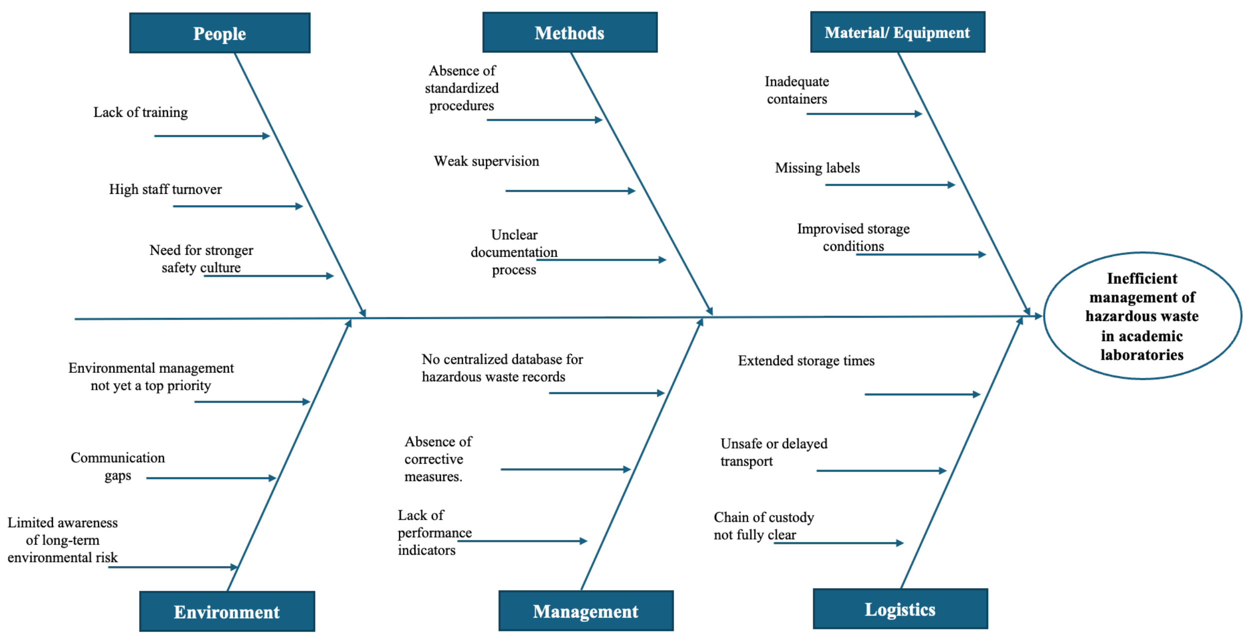

Figure 3. Ishikawa diagram of root causes of inefficient hazardous waste management in academic laboratories

Finally, all collected and structured data were digitized and consolidated into a master database, which served as the foundation for applying the DMAIC methodology. From this database, Key Performance Indicators (KPIs) were calculated, including compliance rate (α), average storage time (β), training coverage (δ), and documentary traceability (ε). The integration of diverse data sources with analytical tools ensured a comprehensive and reliable representation of the current state of hazardous waste management in the university laboratories.

5. Results and Discussion

5.1 Numerical Results

Compliance Level (α) is the most comprehensive KPI, as it measures whether hazardous waste management activities follow established procedures and regulatory standards (Figure 4). It was calculated as the ratio of compliant audited activities to the total audited activities, expressed as a percentage. The optimal benchmark is set at ≥90%, reflecting international standards such as ISO 14001 for institutional reliability. Results showed that compliance in Industrial Engineering increased from 22% in 2024 to 61% in 2025, while Civil Engineering rose from 18% to 78% (Figure 5).

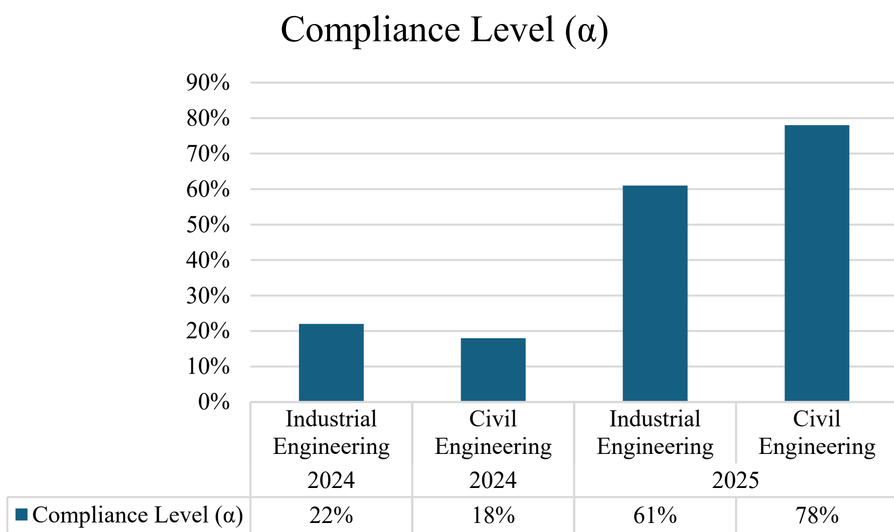

Figure 4. Improvement in Compliance Level (α) for Engineering Laboratories

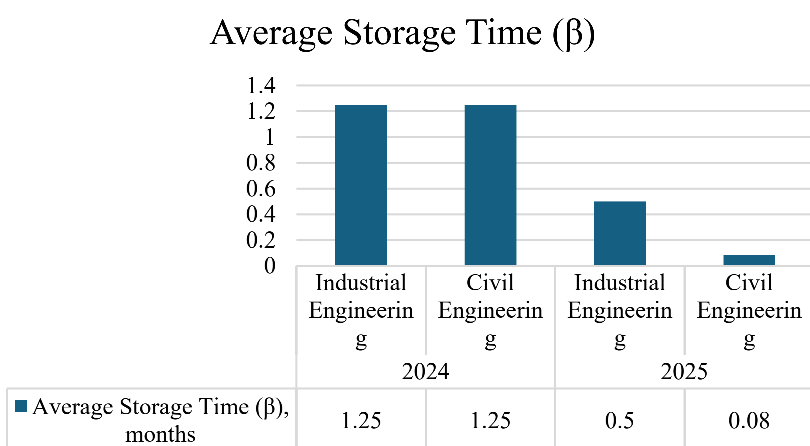

Figure 5. Reduction of Hazardous Waste Storage Time in Engineering Laboratories (2024–2025)

Average Storage Time (β) reflects how long hazardous waste remains stored before safe disposal, a critical factor for minimizing operational, environmental, and safety risks. The indicator was measured as the average number of months that waste was stored, with the legal benchmark in Peru being ≤12 months. In 2024, both programs (Industrial and Civil Engineering) exceeded the standard, with 15 months of average storage. After the implementation of process improvements, Industrial Engineering reduced storage time to 6 months and Civil Engineering to less than 1 month, ensuring compliance and drastically lowering exposure to risk. This outcome highlights the effectiveness of planning, monitoring, and logistical improvements (Figure 6).

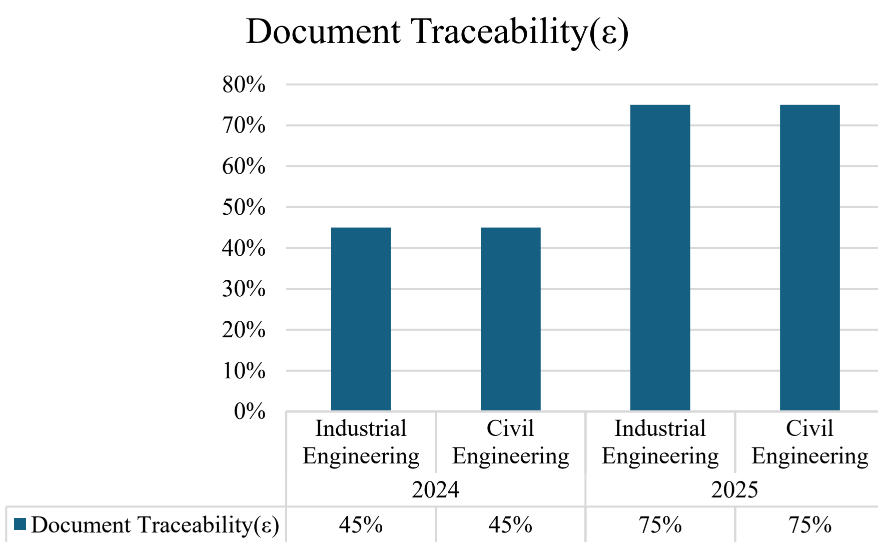

Figure 6. Improvement in Document Traceability (ε) for Industrial and Civil Engineering Laboratories

Document Traceability (ε) measures the percentage of hazardous waste streams that include complete and auditable records from generation to final disposal. This KPI is essential for ensuring transparency, institutional accountability, and compliance with regulatory frameworks, with an optimal benchmark of ≥98%. In 2024, traceability in both programs was limited to 45%, hindered by fragmented reporting systems and the absence of standardized documentation procedures. Following the implementation of digitalized forms and uniform reporting fields in 2025, traceability improved significantly, reaching 75% in both Industrial and Civil Engineering.

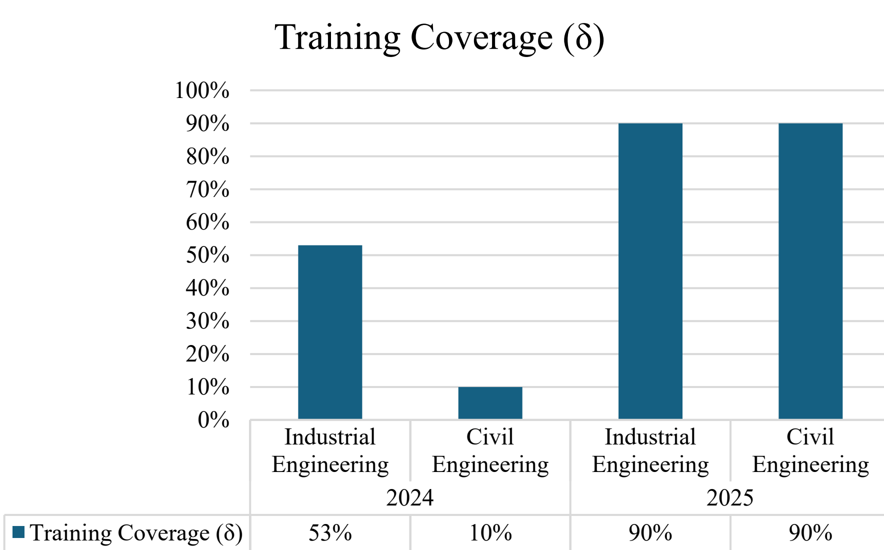

Figure 7. Improvement in Training Coverage (δ) for Engineering Laboratories

Training Coverage (δ) assesses the proportion of laboratory staff, technicians, and assistants who have received formal training in hazardous waste management within the last six months (Figure 7). Since human factors are often the root cause of non-compliance, the optimal benchmark is 100%, ensuring continuous skill development despite staff turnover. In 2024, Industrial Engineering reached only 53% coverage, while Civil Engineering was critically low at 10%. After targeted interventions—including practical workshops, induction modules, and standardized training programs—coverage surpassed 90% in both programs by 2025. This demonstrates that capacity building is not only a corrective measure but also a driver for cultural change and long-term institutional improvement.

5.2 Graphical Results

In addition to quantitative indicators, visual evidence played a critical role in validating the effectiveness of the improvement model. Photographs taken during internal audits documented the transition from unsafe and non-standardized practices to standardized, controlled, and compliant operations. These before-and-after comparisons provide tangible proof that the actions implemented under the DMAIC cycle translated into visible changes in infrastructure, equipment, training, and supervision. The following figures illustrate key areas where the transformation was most evident.

5.2.1 Equipment and Labelling

At baseline, hazardous waste containers were frequently reused, lacked proper labelling, and did not comply with international standards such as the Globally Harmonized System (GHS). This situation created gaps in traceability (ε) and compliance (α), since residues could not be clearly identified or linked to their origin. After the intervention, standardized containers and homologated GHS pictograms were implemented, reaching 70% compliance. This improvement not only facilitated safer handling and internal audits but also strengthened the reliability of documentary control (Table 1).

Table 1. Improvement in Hazardous Waste Containers and Labelling Practices (Before vs. After Implementation)

Before	After
	

5.2.2 Storage Facilities

Initial observations revealed improvised storage spaces with inadequate furniture, lack of signage, and insufficient safety equipment. This condition contributed directly to excessive storage times (β) and increased the risk of exposure to hazardous substances. Following the improvement plan, a central storage facility was equipped with compliant shelving, safety signage, and emergency response systems such as eyewash stations. The visual change illustrates how standardization of infrastructure reduced variability, improved operational safety, and ensured compliance with national regulations (Table 2).

Table 2. Improvement in Hazardous Waste Storage Facilities: From Improvised Spaces to Standardized Central Storage

Before	After
	

5.3 Proposed Improvements

The interventions designed through the Analyze and Improve phases were both technical and organizational, with a focus on sustainability. Four main strategies were deployed:

1. Internal regulation standardization: The CSBQR committee developed a formal internal regulation aligned with ISO 14001 and national regulations (D.L. 1278). This included standardized procedures for waste declaration, labeling, segregation, and storage, with defined roles and responsibilities.
2. Digitalization of declaration forms: Paper-based forms were redesigned and digitalized, incorporating key fields such as waste generator, academic activity, type and hazard classification, and date of generation. This reduced transcription errors, streamlined information flow, and enabled real-time traceability.
3. Comprehensive training program: Training modules were implemented for staff and professors, tailored to their roles. More than 90% of personnel participated in workshops covering chemical identification (MSDS, GHS pictograms), proper segregation, labeling, and storage.
4. Operational support measures: Visual reminders, daily checklists, and clear signage in storage areas were introduced. These low-cost interventions reduced errors, reinforced accountability, and supported continuous compliance.

Together, these improvements addressed both root causes and operational inefficiencies, reducing process variability and establishing a preventive culture in hazardous waste management.

Embedding ISO 14001 review cycles and LCA-informed thinking supports long-term environmental performance rather than one-off audit gains. The combination of standardized procedures, digital traceability, and periodic training consolidates institutional governance and reinforces preventive culture consistent with sustainable development goals (Finkbeiner et al., 2010; Singh et al., 2015).

5.4 Validation

The validation of the proposed model was carried out through internal audits and systematic reviews conducted during 2025 in the laboratories of Industrial and Civil Engineering. At the beginning of the project, the situation revealed significant deficiencies: compliance with national regulations was extremely low, with only 22% in Industrial

Engineering and 18% in Civil Engineering. Hazardous waste was stored for an average of 15 months, far exceeding the 12-month limit established by Peruvian legislation (D.L. 1278). Traceability was nonexistent, since no waste could be tracked across its entire life cycle, from generation to final disposal. In addition, training coverage was limited to 53% of laboratory staff, which increased errors in segregation, reduced the reliability of declarations, and limited awareness of responsibilities among users.

To address this scenario, the Biological, Chemical, and Radiological Safety Committee (CSBQR) led the design and implementation of the improvement project, adapting the DMAIC cycle to the academic environment. The interventions took place in 12 laboratories across Industrial and Civil Engineering, where a combination of actions was applied: the standardization of internal regulations aligned with ISO 14001 and D.L. 1278, the digitalization of declaration forms with expanded fields for generator, academic activity, type of waste, hazard classification, and date of generation, and the introduction of visual reminders and daily checklists. In parallel, a comprehensive training program was implemented, achieving the participation of more than 90% of the laboratory personnel. These measures were complemented by continuous audits and participatory workshops that reinforced a culture of responsibility.

The audits carried out in 2025 confirmed the effectiveness of these actions. Compliance rose to 61% in Industrial Engineering and 78% in Civil Engineering, demonstrating substantial progress compared to baseline levels. Storage times decreased significantly, dropping to less than 6 months in Industrial Engineering and to less than 1 month in Civil Engineering, thereby meeting legal requirements. Traceability improved from 45% to more than 70%, thanks to the implementation of digital records and standardized reporting procedures. Training coverage also exceeded 90%, transforming what was once a critical weakness into a new strength for the institution.

In addition to quantitative results, qualitative evidence collected from laboratory staff reinforced the perception of improvement. Personnel reported that the redesigned procedures, the digital forms, and the training sessions were clearer, easier to implement, and more effective in preventing errors. More importantly, compliance ceased to be perceived as an external imposition and began to be seen as part of academic responsibility and institutional excellence.

In summary, the validation confirmed that the proposed model not only closed critical gaps in compliance and safety but also created the necessary conditions for long-term sustainability. By combining quality methodologies such as DMAIC, Lean, and Six Sigma with environmental tools such as ISO 14001 and the life cycle perspective, the intervention demonstrated that higher education institutions can adapt industrial methodologies to their own context and achieve measurable improvements in hazardous waste management.

5.5 Discussion

Although the results demonstrated significant progress across all key performance indicators, important challenges remain before reaching optimal levels—particularly in compliance, traceability, and full training coverage. As W. Edwards Deming emphasizes, every system is influenced by common causes of variation that cannot be eliminated immediately. In this context, factors such as high staff turnover, fragmented responsibilities, and the inherent complexity of academic laboratories continue to affect the stability of hazardous waste management processes. Recognizing these systemic limitations is essential to ensure that improvement efforts are realistic, sustainable, and aligned with the principles of continuous quality improvement.

These variations do not undermine the achievements but rather highlight the dynamic nature of improvement in a university environment. From a Total Quality Management perspective, the study validates the importance of integrating technical tools (DMAIC, Ishikawa, E-VSM, LCA) with cultural and organizational strategies that strengthen institutional learning. The observed improvements—such as reduced storage times, improved documentation, and increased training coverage—illustrate that even in complex systems, structured quality methodologies can generate measurable, replicable, and high-impact outcomes. However, the limited observation window prevents verifying long-term stabilization, underscoring the need for sustained monitoring and reinforcement of good practices.

Looking forward, future research should deepen the quantitative application of Life Cycle Assessment (LCA) methodologies, such as ReCiPe2016 or SimaPro, to better measure the environmental impacts associated with different waste management practices in universities. It is also recommended to examine the effect of staff turnover on operational sustainability, identifying training and knowledge transfer strategies that guarantee process continuity.

Equally important is the study of organizational culture and its influence on safety and environmental compliance, through qualitative analyses of attitudes and barriers faced by staff and faculty. Finally, more detailed studies on segregation and labeling practices could strengthen the direct relationship between traceability, risk minimization, and institutional compliance.

6. Conclusions

The study demonstrated significant improvements in hazardous waste management within a university setting by integrating ISO 14001, LCA principles, Green Lean, and Green Six Sigma under a DMAIC framework. Compliance levels rose from 22% to 61% in Industrial Engineering and from 18% to 78% in Civil Engineering. The average time that waste exceeded the legal storage limit dropped from 1.25 to 0.5 months in Industrial Engineering and to just 0.08 months in Civil Engineering. Meanwhile, document traceability improved from 45% to 75%, and training coverage increased from 53% and 10% to over 90% in both programs. These outcomes indicate that structured quality methodologies are effective in high-variability academic settings. Beyond numerical improvements, the research underscores the importance of standardization, digitalized records, and role-specific training to embed accountability and reduce operational risk. The work contributes a transferable model for academic laboratories that unifies environmental and quality management, offering clear procedures, KPI monitoring, and feedback loops for continuous improvement. Future studies should expand validation to additional faculties and campuses, test longer observation windows, and incorporate quantitative LCA to estimate avoided impacts. Investigating turnover-resilient training designs and refining segregation and labeling practices will help consolidate compliance and sustainability over time.

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