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Energy Efficiency and Waste Reduction Through Maintenance Optimization: A Case Study in the Pharmaceutical Industry

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Abstract

The global rise in population, increased life expectancy, and heightened international mobility have escalated disease prevalence and pharmaceutical demand. This growth intensifies energy consumption and chemical waste production within the pharmaceutical industry, challenging environmental sustainability and operational efficiency. Chromatography, a vital analytical technique for ensuring product quality and regulatory compliance, can also contribute to material waste and energy inefficiencies if not properly maintained and optimized. This study applies Failure Mode and Effects Analysis (FMEA) to chromatographic equipment maintenance within Hovione's Engineering and Maintenance Department, aiming to identify and mitigate failure risks. By integrating environmental metrics derived from Life Cycle Assessment (LCA) into the FMEA framework, a hybrid risk evaluation tool was developed that prioritizes both equipment reliability and sustainability performance. The findings demonstrate how this integrated approach reduces unplanned downtime, lowers solvent waste, and improves energy efficiency. Additionally, the study proposes a conceptual dashboard to support proactive, sustainability-driven asset management in pharmaceutical laboratories. By bridging reliability engineering and environmental sustainability, this research offers a strategic model for optimizing resource use, minimizing chemical waste, and enhancing long-term operational resilience in regulated pharmaceutical environments.

Keywords: energy efficiency; waste; sustainability; lifecycle; maintenance; process optimization; operational efficiency; biomedical devices; pharmaceutical industry

Academic Editor: Catherine N. Mulligan

Received: 4 July 2025
Revised: 8 August 2025
Accepted: 14 August 2025
Published: 21 August 2025

Citation: Domingues, N.S.; Patrício, J. Energy Efficiency and Waste Reduction Through Maintenance Optimization: A Case Study in the Pharmaceutical Industry. *Waste* **2025**, *3*, 28. https://doi.org/10.3390/waste3030028

1. Introduction

Chromatography is a fundamental analytical and preparative technique widely employed to separate, identify and purify components within complex mixtures, serving both qualitative and quantitative purposes. Its effectiveness derives from the differential interactions of molecular properties—such as size, charge, hydrophobicity, and affinity for the stationary phase—under defined conditions [1]. By comparing chromatograms of known standards with those of unknown samples, analysts can confirm the presence or absence of target compounds. This precision and reliability make chromatography indispensable across sectors such as environmental monitoring, food safety, and clinical diagnostics, as well as in anti-doping controls in sport [2]. In the pharmaceutical, fine chemical and biotechnology industries, techniques such as High-Performance Liquid Chromatography (HPLC) and Gas Chromatography (GC) are particularly valued for their sensitivity, reproducibility, and versatility [3]. Chromatography's significance is underscored by its role in ensuring regulatory compliance and product quality, but it also presents challenges. Instrument operation and maintenance can be resource-intensive, contributing to solvent waste, high energy consumption and the generation of hazardous residues [2].

Pharmaceutical manufacturing is among the most resource-intensive of industrial sectors, demanding high purity standards and subject to stringent regulatory oversight. Production processes typically involve multiple stages—synthesis, purification, formulation, and packaging—each with distinct material, energy, and waste streams. These stages require advanced equipment, often operating under controlled environments, which consume substantial amounts of electricity for heating and cooling energy [4,5]. Sustainability in this context is not simply an environmental aspiration but a regulatory and economic necessity. The "triple bottom line" framework, incorporating environmental, economic and social sustainability, now guides pharmaceutical operations to reduce water and energy consumption, cut greenhouse gas emissions, and minimize waste, while enhancing corporate responsibility and stakeholder trust [6].

Energy use in industrial operations is a major contributor to global greenhouse gas emissions. Within pharmaceutical plants, heating, ventilation, and air-conditioning (HVAC) systems, process compressors, vacuum pumps, and water purification units are among the most energy-demanding assets [7]. Improving energy efficiency in these systems has a dual benefit: reducing operational costs and mitigating environmental impact. One of the most comprehensive tools for assessing such impacts is Life Cycle Assessment (LCA), which evaluates products and processes from raw material extraction through manufacturing, distribution, use, and eventual disposal [8].

Figure 1 illustrates the generic stages of an LCA. Since its emergence in the 1960s, LCA has evolved into a key methodology for guiding improvements in process design, operational optimization and end-of-life strategies, particularly in regulated, high-risk sectors such as pharmaceuticals [9]. The four principal phases of an LCA are: defining the goal and scope; conducting inventory analysis; performing impact assessment; and interpreting results to inform decision-making.

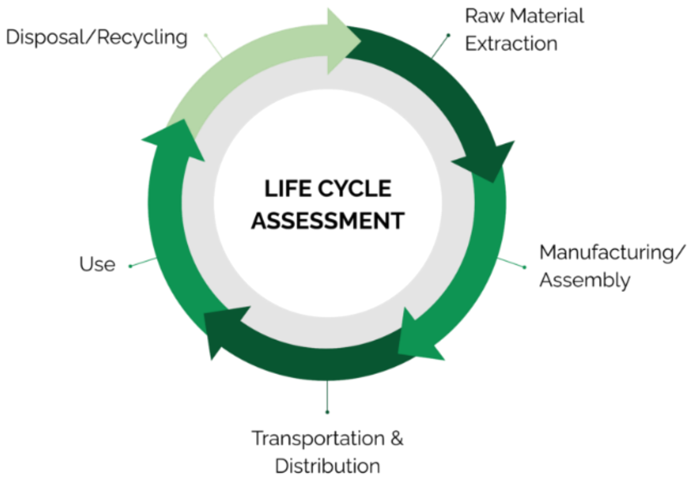

Figure 1. Life cycle analysis [8].

Validation processes complement sustainability objectives by ensuring that systems consistently produce products meeting their predefined specifications. Rooted in U.S. Food and Drug Administration (FDA) guidance from the 1970s, validation provides documented assurance that manufacturing and analytical systems operate as intended, forming a cornerstone of Current Good Manufacturing Practice (CGMP) [10,11]. From process design through performance qualification, validation embeds quality-by-design principles, thereby reducing reliance on end-product testing and enhancing operational robustness.

Maintenance planning is integral to both sustainable and compliant operations. Effective strategies preserve equipment functionality, reduce unplanned downtime and extend asset life, which is critical for high-precision instruments such as HPLC and GC systems. The most suitable maintenance approach for a given asset depends on factors including its criticality, lifespan, budget constraints, and required maintenance frequency [12]. High-criticality equipment—such as analytical chromatographs in pharmaceutical laboratories—requires particular attention due to the potential impact of failures on data integrity, production continuity and regulatory compliance [13].

Maintenance strategies range from corrective (post-failure) to preventive (scheduled) and predictive (condition-based) approaches [14,15]. Predictive maintenance relies on real-time monitoring and diagnostics, allowing interventions only when needed, thereby avoiding unnecessary servicing and reducing waste. However, predictive methods require adequate data—often unavailable for highly reliable components with infrequent failures. In such cases, degradation analysis can estimate remaining useful life without awaiting breakdown [16]. Figure 2, adapted from [17], illustrates an enhanced predictive maintenance methodology that integrates degradation mechanism modeling with failure forecasting.

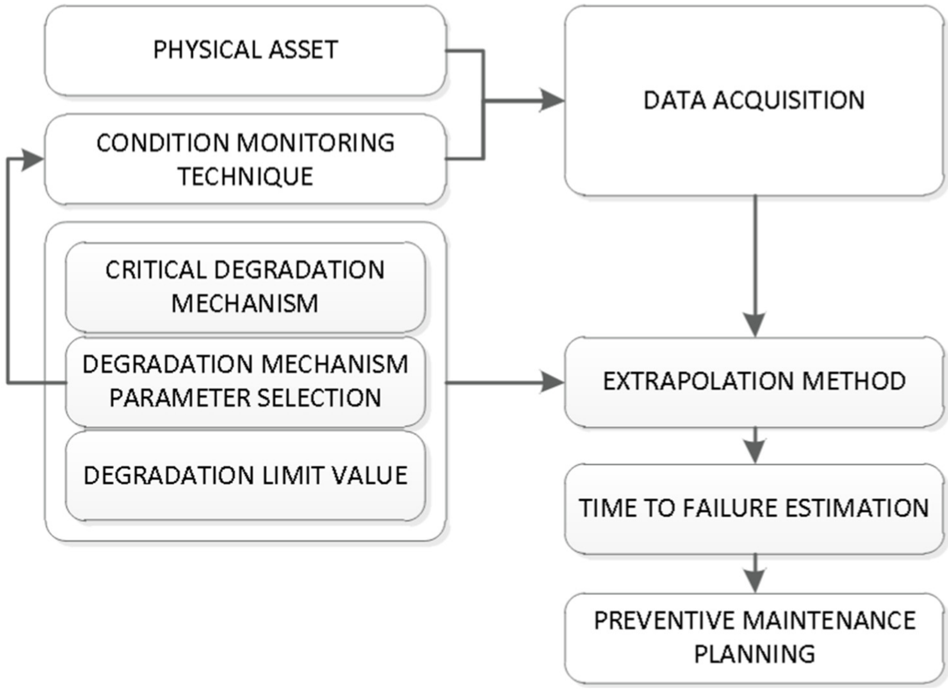

Figure 2. Methodology for degradation mechanism and failure forecast.

In the pharmaceutical sector, where regulatory compliance, product quality, and operational continuity are paramount, the consequences of equipment failure can be severe. Malfunctions may cause production delays, product recalls, or even regulatory sanctions. Therefore, aligning maintenance strategies with environmental objectives is increasingly recognized as best practice. Nevertheless, sustainability literature on pharmaceuticals has historically focused on green chemistry, facility energy efficiency, and packaging [18], with far less attention paid to the environmental implications of analytical instrumentation. This is a significant gap given that chromatography instruments, particularly HPLC systems, account for a disproportionately high share of laboratory solvent consumption and waste generation [19,20].

Analytical devices follow typical life cycle reliability curves, with an initial phase of high failure rates ("infant mortality"), a stable operational phase, and an end-of-life wear-out phase [21]. Understanding this trajectory enables the better alignment of maintenance and environmental strategies, such as replacing solvent-intensive columns earlier or adopting energy-efficient heating elements before performance degradation escalates. Integrating Life Cycle Management (LCM) principles with Failure Mode and Effects Analysis (FMEA) creates a powerful framework for prioritizing maintenance actions not only by their operational risk but also by their environmental footprint [22].

This integrated approach is particularly valuable in regulated pharmaceutical environments. By embedding environmental metrics—such as solvent waste volumes, energy consumption and failure-related emissions—into traditional FMEA, maintenance teams can identify high-risk, high-impact equipment and target interventions accordingly. This alignment of technical reliability with sustainability objectives supports compliance with both CGMP [11] and ISO 14001 [23] standards, while enabling a shift from reactive to predictive maintenance cultures.

In summary, chromatography's pivotal role in pharmaceutical manufacturing makes it both a technical and an environmental focal point. The energy and resource intensity of industrial operations, coupled with the sector's stringent regulatory framework, necessitates maintenance strategies that optimize equipment reliability while reducing environmental impacts. The integration of LCA and FMEA methodologies provides a holistic pathway to achieving these goals, enabling pharmaceutical laboratories to improve operational resilience, reduce waste, and enhance energy efficiency. In doing so, they contribute to broader sustainability targets and to the responsible stewardship of resources in one of the most regulated and impactful industries worldwide.

2. Methodology

This study aims to enhance sustainability in pharmaceutical manufacturing by integrating energy efficiency and waste reduction practices through optimized maintenance strategies. Specifically, it applies Failure Mode and Effects Analysis (FMEA) within the analytical laboratory of Hovione, a Portuguese pharmaceutical company, to identify high-risk biomedical and analytical equipment. By correlating FMEA results with environmental and operational impact metrics—such as energy consumption, solvent waste, and downtime—the research develops a data-driven framework to support proactive, sustainability-oriented maintenance.

Hovione is a globally accredited pharmaceutical laboratory, with facilities in Portugal, Ireland, Macau, and the USA regularly inspected and approved by the FDA, European authorities such as INFARMED and HPRA, and agencies including ANVISA and Japan's PMDA. Many FDA inspections concluded with no Form 483 observations. The company holds EU GMP certificates, ISO 9001:2000 certification, and ICH Q7 compliance, ensuring adherence to stringent international standards. Its quality management system aligns with Eudralex, US 21 CFR, Japanese GMP, and ICH guidelines, reflecting a strong quality culture recognized worldwide.

The scope encompasses 58 laboratory devices, with a primary focus on chromatography systems, including High-Performance Liquid Chromatography (HPLC) and Gas Chromatography (GC). These systems are assessed for their risk priority, environmental footprint, and cost implications. The study also proposes a conceptual Sustainable Lab Operations Dashboard that integrates technical, environmental, and financial key performance indicators (KPIs), offering a scalable model for sustainability monitoring and decision-making in regulated laboratory environments.

This study employs a mixed-method case study design to investigate the intersection of equipment reliability, energy efficiency, and sustainability within the pharmaceutical industry. The research was conducted at the analytical laboratory of Hovione, a Portuguese contract development and manufacturing organization (CDMO), which provides active pharmaceutical ingredients (APIs) and inhalation product development services. The study aims to develop an evidence-based framework for prioritizing maintenance interventions using Failure Mode and Effects Analysis (FMEA), environmental impact metrics, and principles of Life Cycle Management (LCM).

The case study design was selected to enable a detailed, context-sensitive analysis of laboratory operations, offering both theoretical and practical insights. Drawing on methodologies from systems engineering, pharmaceutical quality assurance, and industrial ecology, the study integrates qualitative data (e.g., expert interviews and procedural documents) with quantitative operational data (e.g., failure rates, downtime, and energy use). This multidisciplinary approach aligns with the growing emphasis on sustainable manufacturing practices in high-risk, regulated sectors such as pharmaceuticals [18].

The study focused on a representative sample of 58 biomedical and analytical devices used routinely for quality control and product validation at Hovione. These included high-performance equipment such as High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), ovens, pH meters, microscopes, and refrigerators. Device selection was based on their frequency of use, historical maintenance records, and operational criticality. Data were collected from enterprise resource planning (ERP) systems, laboratory information management systems (LIMS), maintenance logs, and internal standard operating procedures (SOPs), spanning a period of five years.

The core analytical technique employed was FMEA, originally developed by NASA for aerospace engineering and now widely used in manufacturing and healthcare to anticipate and mitigate failure risks. FMEA systematically assesses failure modes based on three dimensions: severity (S), occurrence (O), and detectability (D). Each parameter is assigned a value between 1 and 10, and the product of these values yields the Risk Priority Number (RPN), which provides a quantitative measure of risk ($RPN = O \times D \times S$). In this study, the severity score was fixed at 10 for all equipment, based on the rationale that any malfunction could compromise drug safety, laboratory integrity, or regulatory compliance. The detectability score was set at 1, reflecting Hovione's stringent maintenance protocols, operator training programs, and real-time reporting systems, which together ensure high sensitivity in detecting anomalies. As a result, the occurrence score served as the principal differentiating factor across devices, calculated from empirical failure rates over the study period.

In accordance with Hovione's internal operational and quality assurance policies, fixed values of severity ($S = 10$) and detectability ($D = 1$) were applied in the Failure Mode and Effects Analysis (FMEA) for all laboratory equipment. This approach is justified by the company's zero-tolerance stance on deviations from validated procedures, where any equipment failure—regardless of type—poses a critical risk to drug safety, regulatory compliance, and laboratory integrity, thereby warranting the maximum severity rating. Similarly, the low detectability score ($D = 1$) reflects Hovione's stringent maintenance protocols, continuous operator training, and proactive incident reporting systems, which ensure the near-immediate identification of any abnormal operating conditions. These assumptions are consistently enforced across the organization, as documented in internal standard operating procedures and corroborated by centralized incident management practices. Therefore, the use of these fixed values aligns with established internal standards and ensures the conservative, risk-averse prioritization of maintenance actions in line with both CGMP [11] and ISO 14001 [23] compliance frameworks.

While these assumptions simplify the RPN calculation, they are justified by the company's zero-tolerance policy for deviation from validated processes. Hovione's internal quality protocols mandate that all operational anomalies—regardless of perceived severity—

be documented and escalated via a secure, centralized incident management platform. Only certified professionals are permitted to handle and maintain laboratory equipment, thereby reinforcing a culture of preventive vigilance and procedural discipline.

To enhance the FMEA framework, the study incorporated environmental and operational performance indicators for selected high-RPN equipment. Metrics included average downtime per failure (hours), waste output (liters or kilograms of solvents, packaging, or reagents), energy consumption (kWh), and associated repair costs (euros). These data were compiled from internal monitoring systems, energy audits, technical datasheets, and interviews with laboratory managers and maintenance engineers. Where direct measurements were unavailable, estimates were triangulated using published benchmarks and manufacturer specifications. The integration of environmental parameters into the FMEA matrix provided a multidimensional risk assessment approach, consistent with principles of green maintenance and sustainable asset management [22].

Devices were further contextualized within their respective life cycle stages using the "bathtub curve" model, which characterizes equipment failure patterns across three phases: early-life (infant mortality), mid-life (steady-state performance), and end-of-life (wear-out) [21]. This classification facilitated tailored maintenance recommendations, aligning strategies—corrective, preventive, or predictive—to each device's reliability profile and environmental footprint. Maintenance models were compared not only on the basis of failure reduction but also in terms of their capacity to reduce waste and energy losses over the equipment's operational life.

The "bathtub curve" illustrated in Figure 3 remains a valuable framework for understanding the typical failure patterns of pharmaceutical laboratory equipment, such as HPLC and GC systems. It illustrates the initial phase of early failures due to manufacturing defects, followed by a prolonged period of stable operation, and finally an increasing failure rate as components wear out. However, with advances in sensor technology, data analytics, and the Internet of Things (IoT), Hovione is actively exploring ways to move beyond traditional time-based or age-based maintenance models. By integrating real-time monitoring data from critical equipment, the company aims to enhance predictive maintenance strategies and better anticipate failures before they occur. Currently, select chromatographic instruments are equipped with sensors that monitor parameters such as pump pressure, flow rates, temperature stability, and detector responses. These data streams feed into centralized analytics platforms that apply machine learning algorithms and statistical models to detect early warning signs of degradation or anomalous behavior. For example, subtle deviations in pump pressure curves may indicate impending seal failure, while unusual detector noise might signal contamination or alignment issues.

To synthesize findings and support decision-making, a conceptual digital dashboard—titled the Sustainable Lab Operations Dashboard—was designed. This tool aggregates key performance indicators (KPIs) related to reliability (RPN), environmental impact (e.g., CO_2 emissions, energy intensity), and cost-efficiency. Although not deployed in a live system, the dashboard provides a prototype for future digitalization efforts within the company. Its potential implementation through platforms such as Power BI, Tableau, or Grafana would enable real-time tracking of maintenance activities and sustainability outcomes, supporting compliance with CGMP [11] and ISO 14001 [23] standards.

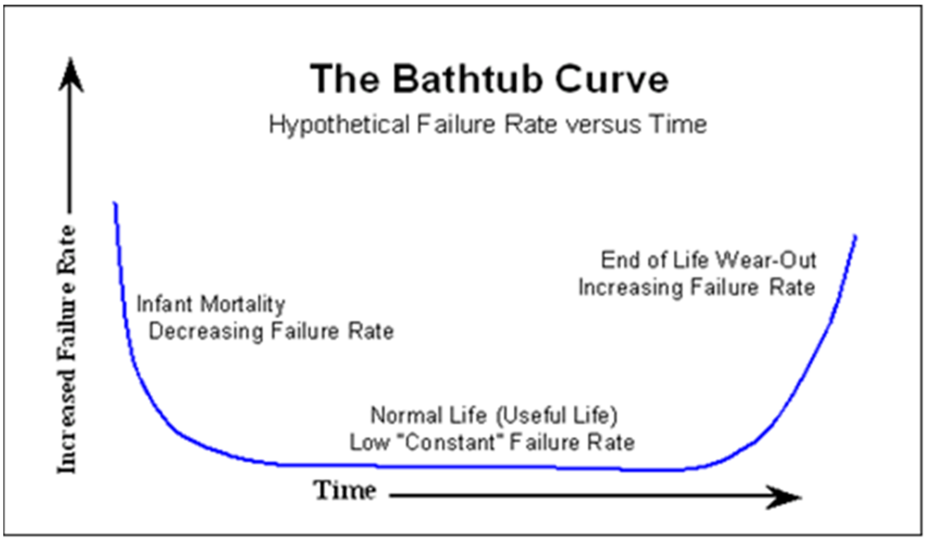

Figure 3. "Bathtub curve" graph [24].

In sum, this integrated methodology offers a replicable and scalable model for laboratories aiming to align equipment reliability with environmental and operational efficiency. By embedding sustainability into core engineering assessments, the approach contributes to a more resilient and resource-efficient pharmaceutical manufacturing process.

The development of a sustainability-focused dashboard in this study provides a practical and scalable tool for operational decision-making within pharmaceutical laboratories. By integrating technical reliability metrics (e.g., Risk Priority Number), environmental indicators (e.g., solvent waste, energy consumption), and financial costs (e.g., downtime and repair expenses), the proposed Sustainable Lab Operations Dashboard enables stakeholders to visualize, prioritize, and act upon equipment maintenance needs with sustainability performance in mind.

From a management perspective, the dashboard enhances transparency by consolidating disparate data sources into a single, accessible interface. This supports cross-functional alignment between engineering, quality assurance, and sustainability teams. Laboratory managers can use the dashboard to identify high-risk, high-impact equipment, justify investments in predictive maintenance, and optimize resource allocation in line with sustainability targets. For example, equipment with high RPN values and significant environmental impacts, such as HPLC systems, can be flagged for early intervention, including the adoption of solvent recovery technologies or workflow redesigns to reduce waste.

The dashboard also supports regulatory compliance and audit readiness. In environments governed by CGMP [11] and ISO 14001 [23] standards, having a data-driven visual tool strengthens documentation, supports continuous improvement, and provides real-time evidence of environmental and operational performance. Moreover, integrating such a system within broader digital infrastructure (e.g., ERP, LIMS, or building energy management systems) can facilitate automated monitoring and reporting, thus reducing administrative burdens and improving responsiveness.

Importantly, the dashboard concept is adaptable to other high-risk sectors where analytical or process equipment plays a critical role, such as biotechnology, food safety, or chemical manufacturing. Its modular design allows for customization based on specific equipment classes, facility goals, or sustainability KPIs, making it a valuable framework for scaling green maintenance strategies across industry settings.

In summary, the proposed dashboard bridges the gap between reliability engineering and environmental performance, enabling pharmaceutical laboratories to shift from reactive maintenance to a proactive, sustainability-informed model of asset management. This contributes not only to operational efficiency but also to broader environmental responsibility and strategic risk reduction.

Although a full Life Cycle Assessment (LCA) was not independently conducted for each device, key LCA principles—particularly those related to resource consumption, emissions, and waste generation—were integrated into the extended FMEA framework to inform both risk prioritization and maintenance strategy design. For high-RPN equipment, environmental metrics such as average energy consumption (kWh), solvent waste (liters), and failure-related carbon impacts were collected or estimated using internal monitoring systems, equipment datasheets, and benchmarked literature. These metrics were not used to adjust the RPN calculation directly, but rather to contextualize it: devices with similar RPNs were further differentiated by their environmental footprint to guide mitigation actions. For example, HPLC systems were identified as both high-risk and high-impact due to their solvent waste and energy use, justifying the proposal of preventive diagnostics and solvent recovery systems. In this way, LCA principles informed a multidimensional prioritization strategy, aligning technical reliability with sustainability objectives and reinforcing the utility of FMEA as a holistic decision-support tool.

3. Results

The case study involved applying FMEA to biomedical equipment in the analytical laboratory at Hovione, in order to obtain a risk priority scale for each type of equipment, as well as to assess how a piece of equipment might fail and the potential impacts on laboratory operations due to that failure. FMEA is a type of risk assessment method created and developed by the National Aeronautics and Space Administration (NASA) in the mid-1960s for the Apollo program. Since then, other major industrial companies in the U.S. have introduced their own assessment systems; however, FMEA is the most common way to evaluate the reliability of a device. It is a preventive reliability assessment method conducted during the design development phase for changes to systems or components of a device, utilizing an empirical perspective for analyzing and making potential changes to components to achieve desired outcomes. It is widely used to assess project, process, and system risks across all sectors. FMEA is advantageous because it allows systematic analyses using simple methods. The evaluation criteria for expected severity, occurrence, and detection are established using the Risk Priority Number (RPN) technique, and the failures of individual components are assessed. These results are combined to obtain criticality. However, the logic is inferior to other methods because it uses qualitative assessment, and the results of the evaluation may vary depending on the experience or preference of the evaluator analyzing the failure. While FMEA relies on qualitative assessments that can be influenced by individual experience and judgment, the study at Hovione implemented several measures to reduce subjectivity and enhance the robustness of the analysis. First, the evaluation process involved a multidisciplinary team comprising engineers, maintenance technicians, and quality assurance specialists, ensuring diverse perspectives and expertise contributed to the scoring of severity, occurrence, and detection parameters. This collective approach helped balance individual biases and fostered consensus-driven ratings. Second, Hovione employed a standardized internal guideline that clearly defined rating scales for each FMEA criterion. These guidelines included specific descriptors and quantitative thresholds wherever possible, for example, categorizing failure occurrence based on historical maintenance records and failure logs, and severity ratings anchored to regulatory impact and process criticality. This structured framework provided consistency and repeatability across evaluations, allowing different evaluators to apply uniform criteria when assessing failure modes. Moreover, calibration sessions were held periodically to review FMEA outcomes and to align interpretations of the rating scales among team members. These sessions helped identify discrepancies early and refine the evaluation approach over time. By combining multiple evaluators with well-defined rating standards and iterative calibration, Hovione effectively minimized subjectivity in the FMEA process, enhancing its reliability as a tool for guiding maintenance prioritization and sustainability efforts.

To conduct a Failure Modes and Effects Analysis (FMEA), a structured sequence of steps was developed. First, all laboratory devices were identified. Subsequently, relevant information was gathered concerning each device's function, operational importance, and mode of use. The analysis then focused on the historical performance of each device, specifically examining the number of failures recorded over a five-year period.

Each identified failure mode was classified according to three key criteria, using a numerical scale from 1 to 10. The probability of occurrence was rated, with a score of 10 indicating a failure mode that is highly likely to occur. The probability of detection was also assessed, where a score of 10 reflects a low likelihood of detecting the failure before it occurs. Finally, the severity of each failure was evaluated, with a score of 10 denoting the most serious consequences in terms of damage or disruption. This classification framework enabled a systematic and quantifiable approach to risk assessment within the laboratory environment.

After this process one can calculate the RPN for each failure mode by multiplying the probability of occurrence by the probability of detection and by severity ("O" × "D" × "S") to obtain a score between 1 and 1000, as shown in Table 1.

Table 1. Calculation for obtaining the RPN (O × D × S) of laboratory devices.

Type	Device	Occurrence	Detectability	Severity	Risk Priority Number
Assistant	Agitators	6	1	10	60
	Conductivity meter	2	1	10	20
	Chronometers	2	1	10	20
	Washing machines	6	1	10	60
	Sealing machine	4	1	10	40
	pH/PG	5	1	10	50
	SPAs	6	1	10	60
	Turbidimeter, viscosimeter, melting point	2	1	10	20
	Water activity, compactor, press	3	1	10	30
	Blankets, drying tree, centrifuge	2	1	10	20
	Rotronic	6	1	10	60
Chromatography	Electrophoresis	6	1	10	60
	Ionic	5	1	10	50
	GC	7	1	10	70
	HPLC	9	1	10	90
	LCMS	5	1	10	50
Diffraction	NIR/IV/UV/Raman	4	1	10	40
	X ray	4	1	10	40

Table 1. *Cont.*

Type	Device	Occurrence	Detectability	Severity	Risk Priority Number
Generic	Jet Sieve, Sieves	3	1	10	30
	Malvern	6	1	10	60
	LAL	2	1	10	20
	Microscope	3	1	10	30
	TOC	4	1	10	40
	Polarimeter	4	1	10	40
	Vitek	3	1	10	30
	Colorimeter	3	1	10	30
	Coulter	2	1	10	20
Inhalation	DT, NGI, ACI	3	1	10	30
Weight	Scales	6	1	10	60
	DSC/TGA	5	1	10	50
Final product	Dissolution	4	1	10	40
	Disintegration	1	1	10	10
	Durometer	2	1	10	20
Temperature	Autoclaves	5	1	10	50
	Refrigerators	6	1	10	60
	Baths	5	1	10	50
	Ovens	7	1	10	70
	Reactor	1	1	10	10
	Thermohygrometer	2	1	10	20
	Ultrasound	4	1	10	40
Titration	KF, KFOven, COU	6	1	10	60
Volume	Flow	3	1	10	30
	Micropipettes, Berettes	6	1	10	60

In this study, the occurrence (O) values in the FMEA were assigned based on historical maintenance and failure data collected over a five-year period from Hovione's internal enterprise resource planning (ERP) and laboratory information management systems (LIMS). Each equipment's failure frequency was calculated based on logged incidents, repair records, and maintenance intervention logs, ensuring that occurrence ratings reflected actual operational performance rather than estimates. To mitigate subjectivity and enhance inter-rater reliability, the evaluation process was conducted by a multidisciplinary team including engineers, technicians, and quality assurance personnel. These experts followed standardized internal guidelines that defined quantitative thresholds for occurrence levels (e.g., failures per month or year). Calibration meetings were held throughout the analysis to align interpretations of the rating criteria and ensure consistency across evaluators. This structured, data-driven approach enhanced the reliability and repeatability of the FMEA results while maintaining compliance with internal quality standards and external regulatory expectations. Inside the Hovione analytical laboratory every single equipment in terms of its criticality is considered to be of maximum level and therefore its "S" will be level 10, as it is assumed that the failure of any of the systems or devices implies a major constraint on daily laboratory activities and can ultimately harm an employee or the customer, as well as the person who receives the final product, which in this case will be the drug or its active ingredient.

Regarding the level of detectability (D), all devices within Hovione's analytical laboratories are subject to robust maintenance protocols and all personnel who operate these devices are frequently called to training sessions on handling and laboratory standards, as well as being encouraged to report any situation that occurs outside the scope of normality in their laboratory practices. These processes have high confidentiality; therefore, given these assumptions, it is assumed for the study of this case that the level of detectability of all laboratory devices is maximum; so it is close to 100% and the value of "D" is 1.

Hovione's internal policy states that all professionals, for this case study one are interested in those who operate their activities in the analytical laboratory facilities, but it is a guideline that extends to all professionals in all areas within the Hovione plant, which orders that any anomaly detected in the normal functioning of the laboratory's daily activities, which can be anything in terms of a malfunction in a device or something more apparently simpler such as a "stain" on the floor, only an employee who is certain of the situation can proceed in order to correct and restore the normal laboratory activity. If the employee detects a certain anomaly and does not know or is unsure of how to resolve it, they must immediately communicate with their superior manager and the incident is notified on the internal occurrence platform. This registration on the platform is always performed by professionals regardless of the severity of the incident and whether they had the skills to resolve it. This policy aims to increase the level of security of the company, both in terms of the security of its human and physical resources and its final products, in addition to maintaining a constant level of alert to prevent adverse situations from occurring. Another policy also contributes to this: only duly qualified professionals can work in the respective areas and operate the indicated equipment, improving their efficiency and extending the useful period within the LCA.

As one can see in Table 1, the most critical devices in terms of maintenance are the HPLC devices with an RPN of 90, followed by GC and ovens, both with an RPN of 70. Although the laboratory's internal policy assumes that any device has a maximum criticality level (S = 10) and because of that no occurrence is tolerable, it is clear that based on these results one are ablet to still assume that there is an order of equipment that is more susceptible to have a failure and with that in mind, more channeling of resources, like financial, the training of professionals, or reviewing protocols for the use and maintenance of this equipment, are something that requires greater reflection and cannot be interpreted as an unnecessary measure.

To correlate RPN with environmental or cost impact, we added impact metrics to our FMEA table, expanding it to include the following columns, as shown in Table 2.

Table 2. Table of added impact metrics to FMEA.

Device	RPN	Avg. Downtime (h)	Waste per Failure (kg or L)	Energy Failure (kWh)	Cost per Failure (€)
HPLC	90	5	3.0 L solvent	8.5	€2000
GC	70	3	2.0 L solvent	6.0	€1500
Oven	70	2	0.5 kg packaging	4.0	€600

To obtain these data, we used historical failure reports (logs, ERP systems), energy/waste monitoring tools, maintenance tickets or equipment OEE data, supplier data sheets and cost of repairs, and discussions with lab managers or operators. To ensure transparency and replicability, the methodology for assigning the FMEA metrics—severity, occurrence, and detection—was carefully structured and documented at Hovione. Severity ratings were determined based on the potential impact of each failure mode on product quality, regulatory compliance, operational continuity, and safety. These impacts were categorized on a scale ranging from minor inconvenience (low severity) to critical failure causing product rejection or regulatory non-compliance (high severity). The criteria were aligned with internal quality standards and relevant pharmaceutical regulations such as CGMP. Occurrence ratings were derived primarily from historical maintenance and failure data collected over multiple years within Hovione's analytical laboratories. By analyzing the frequency of specific failure modes—such as pump malfunctions or detector errors in HPLC systems—evaluators assigned occurrence scores reflecting the likelihood of each failure during typical operation cycles. Detection ratings reflected the probability of identifying a failure before it leads to adverse effects. This was evaluated by reviewing existing monitoring systems, preventive maintenance schedules, and calibration protocols. For example, failure modes detected through real-time diagnostics or regular maintenance checks received higher detectability scores, while those likely to remain unnoticed until causing downtime were rated lower. To support consistency, a detailed internal guidebook was developed outlining explicit definitions and examples for each rating level across the three parameters. The guide included quantitative thresholds where possible, for example, defining "high occurrence" as a failure observed more than once per month or "low detection" as failure modes with no automated alerts or scheduled checks. By grounding the ratings in empirical data, regulatory standards, and standardized guidelines, the study ensured that the FMEA outputs were robust, reproducible, and actionable, providing a solid foundation for maintenance prioritization and sustainability initiatives.

Using this correlation, several strategic benefits can be realized. It enables the improvement of processes and the enhancement of energy efficiency by identifying operational inefficiencies and targeting them for optimization. Additionally, it supports the prioritization of green maintenance strategies, for example, the adoption of eco-friendly solvents in High-Performance Liquid Chromatography (HPLC), thereby aligning maintenance practices with environmental sustainability goals.

The correlation also provides a rationale for upgrading equipment, particularly when existing systems have a high environmental or operational impact. Moreover, it strengthens the justification for investments in predictive maintenance technologies, especially in cases where the return on investment (ROI) is demonstrably high. These insights collectively contribute to more sustainable, cost-effective, and efficient laboratory management.

While our study acknowledges that RPN calculations in FMEA rely on qualitative assessments—making them susceptible to evaluator bias—we did not apply Monte Carlo simulation in this initial research phase. However, integrating Monte Carlo methods could indeed be a valuable extension to address uncertainty and variability in severity (S), occurrence (O), and detection (D) ratings.

The evaluation criteria for expected severity, occurrence, and detection are established using the Risk Priority Number (RPN) technique, and the failures of individual components are assessed. These results are combined to obtain criticality. However, the logic is inferior to other methods because it uses qualitative assessment, and the results of the evaluation may vary depending on the experience or preference of the evaluator analyzing the failure. By conducting simulations in which probabilistic distributions are assigned to the FMEA parameters—reflecting plausible ranges informed by expert input rather than relying on single-point estimates—Monte Carlo analysis can be used to generate a distribution of possible Risk Priority Number (RPN) values, rather than a single fixed score. This probabilistic approach offers several advantages.

It enables the quantification of uncertainty in risk prioritization, providing a more nuanced understanding of potential failure impacts. It also helps to distinguish between failure modes with robust risk rankings and those whose rankings are highly sensitive to evaluator judgment. In doing so, this method allows for more confident resource allocation by explicitly incorporating variability in expert opinions into the decision-making process.

The implementation of such a probabilistic FMEA approach would require the collection of adequate data to define realistic input distributions. It may also involve engaging multiple evaluators to calibrate the parameter ranges effectively. Nonetheless, this represents a promising direction for enhancing the methodological rigor and reproducibility of FMEA, particularly in highly regulated, data-intensive environments such as pharmaceutical manufacturing.

Table 3 shows an example of insights that this analysis identifies.

Table 3. Example of insights of the practical study.

Insight	Implication
HPLC has highest RPN and highest solvent waste.	Justify investing in solvent recovery system or preventive diagnostics.
Ovens cause less downtime but high energy loss.	Retrofit with energy-efficient units.
GC failures are moderate RPN but very costly.	Focus on training and SOP standardization.

Currently, select chromatographic instruments at Hovione are equipped with sensors that continuously monitor critical parameters such as pump pressure, flow rates, temperature stability, and detector signals. These data streams are integrated into centralized analytics platforms, where machine learning algorithms and statistical models analyze the information to identify early signs of equipment degradation or anomalous behavior. For instance, subtle shifts in pump pressure patterns may signal an impending seal failure, while irregular detector noise can indicate contamination or misalignment issues. By leveraging this real-time data, Hovione is transitioning from fixed-interval or reactive maintenance toward condition-based strategies. This shift not only minimizes unplanned downtime and repair costs but also effectively "flattens" the classic bathtub curve by prolonging the stable operational phase, delaying wear-out failures, and reducing unnecessary preventive interventions. In the pharmaceutical industry, where stringent standards for purity, data integrity, and regulatory compliance prevail, predictive maintenance is especially crucial. It ensures continuous analytical performance, maintains product quality, and optimizes resource utilization—key factors for sustaining competitive advantage and meeting rigorous regulatory demands. Looking ahead, Hovione plans to broaden sensor coverage and enhance its data analytics infrastructure to develop a comprehensive digital twin of its laboratory equipment. This advancement will enable even more accurate failure predictions, incorporate environmental impact assessments, and facilitate dynamic, sustainability-focused maintenance scheduling.

Designing dashboards for sustainability KPIs in the pharmaceutical lab context (based on your FMEA + waste + energy focus) involves combining technical, operational, and environmental indicators into a clear, interactive format is key. Below is a comprehensive dashboard design concept tailored to the case at Hovione. The Dashboard Layout, named "Sustainable Lab Operations Dashboard" is organized as follows:

- Sections:
    1. Overview (Executive Summary)
    2. FMEA Risk Monitoring
    3. Environmental Impact
    4. Energy Efficiency
    5. Cost and Resource Allocation

6. Maintenance and Downtime Tracker

1. Overview (Executive Summary)
   - Purpose: Provide quick insights for managers and sustainability officers.
   - Metrics to Display:
     - Total Lab Equipment: 58
     - High-Risk Devices (RPN > 60): 7
     - Estimated Annual Waste (L/kg): e.g., 2300 L
     - Energy Use (kWh/year): e.g., 210,000
     - Maintenance Cost (EUR): e.g., 45,000/year
     - Carbon Footprint (tons CO_2e): e.g., 16.5

   Visualization: Summary cards + color-coded KPI badges (green/yellow/red).

2. FMEA Risk Monitoring
   - Purpose: Track and prioritize equipment based on RPN.
   - Metrics:
     - Risk Priority Number per device;
     - Severity; occurrence; detectability.
   - Features:
     - Filter by equipment type (e.g., HPLC, oven, GC);
     - Drill-down into failure history.
   - Visuals:
     - Heatmap: RPN by device category;
     - Bar chart: Top 10 highest RPN devices;
     - Risk matrix (S vs. O, color = RPN).

3. Environmental Impact
   - Purpose: Link failures and equipment to emissions, waste, and materials usage.
   - Metrics:
     - Solvent waste per equipment;
     - CO_2 emissions per process;
     - Water use (L);
     - Waste per failure (kg/event).
   - Visuals:
     - Pie chart: Contribution to total lab waste by device type;
     - Line graph: Monthly waste trends;
     - Bubble chart: Equipment (x = RPN; y = waste; size = energy use).

4. Energy Efficiency
   - Purpose: Analyze energy use and detect inefficiencies.
   - Metrics:
     - Energy per device (kWh/month);
     - Peak usage times;
     - Comparison to benchmark/targets.
   - Visuals:
     - Gauge: % of energy target achieved;
     - Stacked area chart: Energy use by category (heating, analysis, ventilation);
     - Sankey diagram (optional): Flow of energy from input to devices.

5. Cost and Resource Allocation

- Purpose: Track maintenance costs and align with sustainability outcomes.
- Metrics:
  - Maintenance spend per device;
  - Downtime cost (EUR);
  - ROI of sustainable upgrades.
- Visuals:
  - Horizontal bar: Maintenance cost vs. impact avoided;
  - ROI scatter plot: Cost vs. waste/emissions reduced;
  - Resource allocation pie: Budget % by equipment category.

6. Maintenance and Downtime Tracker
   - Purpose: Reduce unplanned downtime, optimize maintenance.
   - Metrics:
     - MTBF (mean time between failures);
     - MTTR (mean time to repair);
     - Planned vs. unplanned maintenance ratio;
     - Technician response time.
   - Visuals:
     - Timeline: Failure events with severity markers;
     - Gantt chart: Scheduled maintenance activities;
     - KPI dials: Availability; MTBF trends.

To support the development of the dashboard, several implementation tools are recommended, as outlined in Table 4. These tools were selected based on their suitability for data integration, visualization, and real-time monitoring, all of which are essential for an effective and user-friendly dashboard.

Table 4. Tools for the implementation of the dashboard.

Tool	Use Case
Power BI/Tableau	Ideal for interactive visuals and real-time data.
Excel	Static but simple dashboards for internal use.
Grafana	If integrating live sensor/IoT data (e.g., temperature, energy use).
Looker Studio (Google Data Studio)	Web-based, accessible to wider teams.
Qlik Sense	For larger enterprise deployments.

The Dashboard benefits are as follows:

- Identify which high-risk equipment contributes most to emissions or waste.
- Justify investments in energy-efficient upgrades or predictive maintenance.
- Improve audit readiness for GMP and ISO 14001 compliance.
- Support data-driven decisions for sustainability funding and training.

For the high-risk equipment identified—High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), and laboratory ovens—the study revealed distinct failure modes contributing to their elevated Risk Priority Numbers (RPNs). In HPLC systems, pump failures were the predominant issue, often caused by seal wear and blockage in solvent delivery lines, leading to inconsistent flow rates and pressure fluctuations. Detector malfunctions, such as lamp degradation or baseline noise, also contributed significantly to downtime, affecting sensitivity and accuracy. Column degradation, although less frequent, resulted in compromised separation performance and necessitated costly replacements. Gas Chromatography units faced frequent injector failures, often related to septum leaks or liner contamination, which led to sample loss and reproducibility problems. Detector issues, including flame ionization detector (FID) instability and electronic faults, further impacted operational reliability. Laboratory ovens primarily exhibited thermostat malfunctions and uneven temperature distribution due to sensor drift or heating element failures, causing process inconsistencies and delayed analytical results. By pinpointing these specific failure modes, the study provides targeted maintenance priorities, such as implementing preventive seal replacements for pumps, scheduled detector calibrations, and regular cleaning protocols for injector components. These focused interventions not only enhance equipment uptime but also reduce solvent waste and energy consumption, aligning operational efficiency with sustainability objectives.

4. Discussion

The findings of this study confirm the critical role of chromatography equipment—particularly High-Performance Liquid Chromatography (HPLC) systems—in determining both operational reliability and environmental performance in pharmaceutical analytical laboratories. The application of Failure Mode and Effects Analysis (FMEA) identified HPLC units as having the highest Risk Priority Number (RPN = 90), followed by Gas Chromatography (GC) systems and laboratory ovens (RPN = 70 each). This ranking reflects not only the frequency and severity of failures but also the environmental consequences of such events, including significant solvent waste, elevated energy consumption, and extended downtime.

These results are consistent with previous reports that chromatography instruments are among the most failure-prone assets in pharmaceutical laboratories [7]. Common HPLC failure modes—such as pump seal wear, detector malfunctions, and column degradation—are operationally disruptive and contribute to chemical waste generation [19]. Solvents are a major component of laboratory consumables with a high environmental burden, meaning that even modest reductions in solvent loss per failure event can lead to substantial cumulative environmental benefits.

The integration of Life Cycle Assessment (LCA) principles into the FMEA framework allowed for environmental impacts to be considered alongside technical reliability. This approach reflects current trends towards more holistic asset management strategies that unite quality, operational efficiency, and sustainability objectives [6,18]. Adding environmental metrics—such as waste per failure and energy consumed during downtime—enabled differentiation between equipment with similar RPN values but varying sustainability profiles, making maintenance prioritization more precise when resources are limited.

Ovens emerged as high-RPN assets largely due to their energy inefficiency, despite causing relatively short downtimes. This finding supports literature emphasizing that heating elements and thermal control systems can contribute disproportionately to a facility's energy-related greenhouse gas emissions [5,7]. Retrofitting with energy-efficient components or optimizing use schedules could therefore be both cost-effective and environmentally beneficial.

From an operational perspective, the results highlight the potential of condition-based and predictive maintenance strategies for high-criticality equipment. At Hovione, sensor-based monitoring is already partially in place and could support a shift from fixed-interval servicing to predictive interventions, reducing unnecessary maintenance, minimizing waste, and extending equipment life. These findings are in line with Industry 4.0 developments, where IoT integration and machine learning-based monitoring have been shown to reduce downtime and improve resource efficiency

Implementing the proposed Sustainable Lab Operations Dashboard at Hovione, however, presents notable challenges. A primary hurdle is the integration of data from diverse and siloed sources—chromatographic instruments, maintenance logs, energy monitoring systems, and waste management records often reside in separate platforms with different formats and update frequencies. Achieving seamless interoperability would require robust data standardization protocols, real-time acquisition capabilities, and possibly custom middleware, all of which demand significant time and technical resources. Initial investment costs also present a barrier: deploying advanced sensors, upgrading IT infrastructure, and developing analytics software requires substantial capital. In budget-constrained environments, convincing stakeholders to prioritize these investments necessitates a clear demonstration of benefits, such as projected reductions in downtime, waste, and compliance risk. Additionally, the development and maintenance of the dashboard would require multidisciplinary expertise in industrial processes, IT systems, and data science—resources that may be scarce without targeted recruitment, training, or strategic partnerships.

A phased implementation strategy, starting with high-priority equipment such as HPLC systems, could address these barriers by enabling gradual refinement of data integration workflows and providing early proof of concept. Leveraging existing enterprise systems and adopting industry-standard data exchange protocols could streamline integration, while collaboration between IT specialists, maintenance engineers, and laboratory staff would help ensure the tool meets practical operational needs. Clear communication of benefits, coupled with incremental deployment and cross-functional teamwork, could mitigate the risks associated with large-scale adoption.

The applicability of the integrated FMEA–LCA framework extends beyond a single organization. In transferring the approach to other pharmaceutical companies or precision industries, several contextual factors should be considered. Regulatory frameworks vary across jurisdictions and may require adjustments to risk assessment criteria, documentation protocols, and validation processes. Production scale and complexity influence both the granularity and scope of analysis: large operations may require sophisticated analytics and extensive data integration, while smaller facilities may benefit from simplified assessments. Digital maturity also plays a decisive role. Organizations with advanced IoT-enabled systems can more readily deploy real-time monitoring and predictive analytics, whereas those with limited digitalization may need to start with baseline data collection and manual assessments before advancing to automated solutions.

Human factors are also central to the success of this framework. Operator competence and adherence to Standard Operating Procedures (SOPs) directly influence both occurrence and detectability ratings within the FMEA. At Hovione, targeted training on chromatography best practice, preventive maintenance, and troubleshooting, combined with initiatives that encourage timely anomaly reporting, have improved both equipment reliability and early detection rates. This alignment of workforce capability with sustainability objectives underscores the importance of embedding human performance metrics into environmental reporting, reinforcing the link between people and sustainable process performance.

The identification of HPLC systems as the highest-risk category corresponds with broader industry observations that chromatographic processes account for a substantial proportion of solvent use and associated emissions in laboratory environments [19]. The combination of FMEA with LCA-derived environmental indicators reflects emerging best practice in sustainable pharmaceutical manufacturing. The shift toward predictive maintenance, supported by real-time data, is consistent with smart manufacturing trends that have achieved measurable reductions in downtime and operational costs.

While the qualitative nature of FMEA scoring introduces subjectivity, the use of multidisciplinary evaluation teams and standardized internal guidelines mitigated this risk. Nevertheless, incorporating probabilistic modeling techniques, such as Monte Carlo simulation, could strengthen the robustness of future assessments by quantifying uncertainty. Similarly, expanding the use of direct measurements for environmental metrics would improve the accuracy of impact estimates, supporting even more targeted maintenance and sustainability interventions.

Overall, the integrated FMEA–LCA approach demonstrated here provides a replicable and adaptable model for aligning technical reliability with environmental sustainability. The evidence indicates that targeted, sustainability-informed maintenance interventions—particularly for chromatography equipment—can deliver measurable improvements in waste reduction, energy efficiency, and long-term operational resilience. In this way, environmental and operational performance emerge not as competing priorities, but as mutually reinforcing outcomes in modern pharmaceutical asset management.

The study [25] presents a proposal for evolution of these methods by integrating traditional with more recent, by aligning preventive maintenance with industry 4.0. The study [25] contributes by mapping common faults in electric machines and reviewing condition monitoring techniques, highlighting how IoT and AI enable real-time, cost-effective maintenance within Industry 4.0 to enhance efficiency and reduce operating costs.

5. Conclusions

This study identified High-Performance Liquid Chromatography (HPLC) systems as the most critical assets in a regulated pharmaceutical laboratory, followed by Gas Chromatography (GC) systems and laboratory ovens. Using an enhanced Failure Mode and Effects Analysis (FMEA) integrated with Life Cycle Assessment (LCA) principles, the research linked technical reliability with environmental performance, enabling maintenance prioritization based on both operational risk and sustainability impact.

Findings show that failures in chromatography equipment contribute significantly to solvent waste, energy consumption, and downtime. Targeted, sustainability-informed maintenance—particularly predictive and condition-based approaches—can reduce these impacts, improve equipment uptime, and support compliance with CGMP and ISO 14001 standards.

The proposed Sustainable Lab Operations Dashboard offers a framework for visualizing and managing equipment performance, environmental metrics, and costs in real time. While implementation challenges include data integration, investment requirements, and skills gaps, phased deployment and cross-functional collaboration can support successful adoption.

By embedding environmental considerations into reliability analysis, this study demonstrates a practical pathway for pharmaceutical laboratories to enhance resource efficiency, reduce waste, and strengthen long-term operational resilience. The approach is scalable and adaptable to other high-precision, regulated industries seeking to align asset management with sustainability objectives.

Author Contributions: Conceptualization, N.S.D.; Methodology, N.S.D.; Software, N.S.D.; Validation, N.S.D.; Formal analysis, N.S.D.; Investigation, N.S.D., J.P.; Resources, N.S.D.; Data curation, N.S.D., J.P.; Writing—original draft, N.S.D., J.P.; Writing—review & editing, N.S.D.; Visualization, N.S.D.; Supervision, N.S.D.; Project administration, N.S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. However, the internship of the student that is co author of this paper was funded by the company Hovione-Portugal.

Data Availability Statement: All information and data can be provided upon request to the corresponding author.

Acknowledgments: We would like to thank the company Hovione Portugal, namely Engineering & Maintenance Senior Manager Leandro Martins, for providing the data for the analyses and for the student support.

Conflicts of Interest: The internship of the student that is coauthor of this paper was supported by the company Hovione, Portugal. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CGMP	Current Good Manufacturing Practice
CM	Corrective Maintenance
EA	Effect Analysis
FM	Failure Mode
FMEA	Failure Mode and Effect Analysis
GC	Gas Chromatography
HPLC	High-Performance Liquid Chromatography
LCA	Life Cycle Analysis
PdM	Predictive Maintenance
PM	Preventive Maintenance
RPN	Risk Priority Number

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