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Evaluating Environmental Risks and Waste Management in Chemistry Laboratories: Integrating FMEA and Cleaner Production

Avaliação de Riscos Ambientais e Gerenciamento de Resíduos em Laboratórios de Química: Integrando FMEA e Produção Mais Limpa

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Abstract

The issue of environmental waste production has increased substantially, and educational institutions have become initiating agents because of their research and practical activities. This research work has the following objectives: To assess and analyze the environmental aspects and environmental impacts created by the chemistry laboratories at the Institute of Health and Biotechnology (IHB) in Coari, Amazonas, using management methodologies. The FMEA and Cleaner Production (CP) approaches were applied for risk assessment and decision-making to identify risks and propose preventive measures. It becomes clear that the Environmental Risk Index (ERI) guides activities toward managing or reducing risk. In the 67 cases of the process, 32 of them were assessed as priorities, two of which are high risk and require action. The results include the following objectives for a Waste Management System (WMS) suited to the environment in the institution: compliance with current environmental laws or regulations and the creation of a safer environment for students to work and learn.

Keywords: FMEA. Cleaner Production. ERI. Environmental aspects and impacts.

Resumo

A questão da produção de resíduos ambientais tem aumentado substancialmente e as instituições de ensino tornaram-se agentes iniciadores devido às suas pesquisas e atividades práticas. Este trabalho de pesquisa tem os seguintes objetivos: Avaliar e analisar os aspectos ambientais e os impactos ambientais gerados pelos laboratórios de química do Instituto de Saúde e Biotecnologia de Coari, Amazonas, utilizando ferramentas de gestão. As abordagens FMEA e Produção Mais Limpa (CP) foram aplicadas para avaliação de riscos e tomada de decisão para identificar riscos e propor medidas preventivas. Torna-se claro que o Índice de Risco Ambiental (IRA) orienta as atividades no sentido de gerir ou reduzir o risco. Nos 67 casos do processo, 32 deles foram avaliados como prioritários, dois dos quais são de alto risco e requerem ação. Os resultados incluem os seguintes objetivos para um Sistema de Gerenciamento de Resíduos adequado ao meio ambiente na instituição: cumprimento das leis ou regulamentos ambientais vigentes e a criação de um ambiente mais seguro para o trabalho e aprendizagem dos alunos.

Palavras-chave: FMEA. Produção Mais Limpa. IRA. Aspectos e impactos ambientais.

1. Introduction

There is little doubt that environmental sustainability has been a significant issue within organizations, governments, and educational institutions in the last few decades. Pollution associated with industrial processes, deforestation, and waste disposal is worsening rates of depletion of resources and pollution. Another area of significant concern is the subject of environmental management, and this cuts across the handling, treatment, and disposal of waste in different forms because of human activities. Managing this waste is especially important for learning institutions, especially those that offer research and practical laboratories where dangerous waste may be disposed of. Science and knowledge must be delivered to human society and can be produced only by academic work in universities based on scholarly research.

Nevertheless, these developed activities also generate various kinds of waste; if these wastes are not adequately treated, they are fatal to the life of the environment. They are expected to dispose of chemical, biological, and hazardous waste, which is dangerous if handled poorly in laboratories. Schools, colleges, and universities have an ethical and legal obligation to ensure that each waste produced or disseminated by these agencies is done to a minor effect on the environment and under legal provisions.

The Institute of Health and Biotechnology (IHB) chemistry laboratories are not exempt from this responsibility; they are in Coari, Amazonas. IHB laboratories are involved in research and practical analysis in the discipline of chemistry, and to conduct such studies, a number of chemical compounds and reactions are used, and in the process, waste is produced. More particularly, waste management from these laboratories must be effectively handled so that the waste does not hurt the environment and the health of students and staff or the community in which the laboratories are established. Should any of these not be rectified, there is the potential to pollute the soil and water and encounter dangerous substances that may harm both the environment and people handling the products. Later, there are severe penalties for organizations and companies that fail to observe the environmental laws and policies of the country. The best strategy for dealing with environments in laboratories is the assessment of environmental concerns and the effects of their work. That same source from Brazil defines *environmental aspects* as the elements of an organization with activities that can interact with the environment and environmental impacts as the changes that occur in the environment from those interactions as defined by ISO 14001 (International Organization for Standardization [ISO], 2015). There are specific aspects of the organization and its activities with direct impacts on the environment that need to be identified in a systemized manner to improve environmental performance and to set up an Environmental Management System (EMS) for managing environmental risks, optimizing resources, and ensuring compliance with legal requirements.

Applying systemized approaches, such as Failure Mode and Effects Analysis (FMEA) and Cleaner Production (CP), can widely help detect, assess, and control the impacts of environmental concerns on academic institutions. FMEA, or Failure Mode and Effects Analysis, a tool with an industrial origin, is a methodology that helps to determine failure modes in a process, product, or system and rate the failure's severity, occurrence, and detectability. The authors admit that with the help of FMEA, risks can be prioritized, and preventive or corrective actions can be taken to eliminate unfavorable environmental effects. This tool has also been integrated into laboratories for use in the identification of risks that may be associated with the generation of waste, spillage of chemicals, and other related dangers. Another valuable method for increasing environmental performance in laboratories is CP. CP is the ongoing effort to eliminate waste in its production processes and operations, using fewer resources while delivering more results. Applying to chemistry laboratory facilities, CP may include decreasing dangerous reagents, increasing energy usage effectiveness, and recycling or reusing materials. The format involving CP practices is effective because it helps avoid negative impacts on the environment and makes a lab more cost-efficient and safer for learners and staff members.

It has been established that employing both FMEA and CP has a positive impact on directing improved environmental management. For instance, FMEA assesses laboratory activities to identify areas prone to failures or inefficiency. In contrast, using CP offers methods of averting these failures or inefficiency by putting in place better approaches. The synergistic integration of these methodologies increases the effectiveness of institutional capability to develop sound waste management systems that respond not only to current environmental challenges but also address future consequences. These methodologies are especially relevant in the Brazilian legal system since institutions are obliged by laws to follow environmental laws at the federal and state levels. According to the National Policy on Solid Waste (Law No. 12.305/2010), there are guidelines for hazardous and non-hazardous waste; institutions must accept their waste output and integrate improvements in minimization, recycling, and disposal. The latter remains relevant as many educational institutions fail to adhere to such regulating norms to prevent fines and guarantee long-term solvency. Apart from compliance, environmental management in academics involves social responsibility. It is necessary to underline that universities and research institutes are not only sources of knowledge but also responsible for the perceptions of future professionals. Due to this, they promote the culture of environmental sustainability among the institutions' learners, staff, and society. In addition, the outreach of environmental commitments will add value to the institution and become an indicator of global leadership in the fight against environmental issues.

Therefore, this cross-sectional study proves beyond doubt the extent of environmental management practices observed in laboratories. However, it also points to a significant need for support in implementing waste management programs in many institutions. One of the primary challenges recognized is the need for more awareness and appreciation of the environmental hazards involved in laboratory activities. Such findings further underscore the relevant literature recommendations that laboratory personnel need adequate waste management training and adequate resources to give the best. The study also shows that laboratories use many chemicals and apparatus, making it nearly impossible to establish fixed approaches to dealing with the waste produced in these facilities.

Based on these challenges, this article aims to identify environmental risks in the chemistry laboratories at IHB after using FMEA and CP methodologies. Consequently, through a detailed examination of the laboratory processes, this research study will evaluate the environmental aspects and impacts to establish solutions to high-risk activities and develop a waste management strategy to match the institution's needs. The discovery from this study will extensively benefit other academic institutions that grapple with similar challenges and will propel the discussion of eco-friendly waste management in learning institutions.

The purpose of this article is threefold: to describe and assess the environmental aspects and impacts of chemistry laboratories at IHB through the FMEA tool and CP approach. In this sense, the following goals have been proposed within the context of this article: to identify the risks associated with laboratory activities and to provide recommendations regarding these risks and the way to address them to facilitate the establishment of an integrated Waste Management System (WMS) and encourage sustainability at the institution level. This article has several parts to it. The background of the intended study is given, and aspects regarding the effectiveness of environmental management in academic laboratories are discussed to give readers background knowledge that sorts a kind of review before highlighting the specific objectives of the intended study. In the paper, the procedure of FMEA and CP application in the IHB laboratories is described, as well as the data gathering and analysis procedures. This literature review presents data on published works and theories covering environmental management and waste management, together with the application of FMEA and CP in laboratories. The study's results, which involved the classification and prioritization of environmental risks and suggestions on how waste can be better managed, are highlighted in this section of the study. The last section of the present study is the conclusion, which offers a short resume of the major findings of the present study and some suggestions about the future development of this line of research.

2. Literature Review

This section reviews key concepts and methodologies related to waste management, environmental impacts, and the application of management tools like Failure Mode and Effects Analysis (FMEA) and Cleaner Production (CP). These concepts form the theoretical foundation for understanding how waste management can be improved in academic laboratories, such as the IHB.

2.1 Laboratory Waste and Environmental Impact

Laboratory waste is a significant concern in academic institutions due to the diverse materials used in teaching and research activities. According to Teixeira et al. (2012), laboratory waste can include chemical, biological, and health-related materials, posing considerable risks to human health and the environment if improperly managed. These materials may be hazardous, non-hazardous, or infectious and can exist in various forms, such as solid, liquid, or gas. When released into the environment without proper treatment, laboratory activities generate waste that can contaminate water, soil, and air.

Figueiredo et al. (2011) emphasize that waste from practical laboratory activities can have long-lasting environmental impacts if not handled correctly. These impacts range from immediate health risks, such as exposure to toxic chemicals, to long-term ecological damage, such as the contamination of natural resources. Reduce, Reuse, Recycle has become a norm for the institutions to practice not only because it is the law, but it is now part of sustainability concern.

2.2 Environmental Aspects and Impacts

The evaluation of environmental aspects and their impacts involves the following: If an organization is to design, implement, and maintain an appropriate EMS, planning, and identification of environmental aspects and their respective impacts are compulsory. In your opinion, what would be your critique of the assertion by Barbieri (2011) that the first step towards minimizing an organization’s impact on the environment is an evaluation of the environmental impacts of the organization’s activities? This process involves understanding how inputs (such as raw materials, energy, and water) and outputs (such as emissions, waste, and effluents) interact with the environment.

Sánchez (2006) defined *environmental aspects* as the drivers for environmental change and Environmental Impacts as the effects of the aspects. For instance, using chemicals in a laboratory is an environmental aspect, while the potential contamination of local water sources from improper chemical disposal is an environmental impact. Sánchez (2006) also notes that understanding this relationship is crucial for developing strategies to mitigate negative impacts. According to the Federal Constitution of the United Brazilian Republic (1988) and Brazilian Environmental Policy Law (Law 6938, 1991), harming the environment by interference with its balance is prohibited. Environmental consequences of university laboratories can be significant because of the nature of the materials and processes that could be employed in research. Extending from it, Guedes et al. (2011) stress that, although research activities contribute to societal welfare in that they possess some value addition, they produce several types of waste that pollute the environment if not managed appropriately. The intended disposal of these compounds can adversely affect the general health of individuals and the environment since highly toxic compounds may find their way into natural systems.

2.3 Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is a structured tool used to pinpoint the possibilities of failure in production processes and assess the risks of error occurrence. Initially proclaimed in the nineteenth, the FMEA methodology was used to trigger the product and process quality in industrial settings. Following the works of Brand et al. (2013), the FMEA approach that identifies product problems has been the cornerstone of improved practices and services, followed by preventive or corrective actions to mitigate risks. The usage of FMEA was started in the areas of environmental management, where companies could go to to render those activities that cause a threat to the environment. The principal analysis of FMEA comprises severity (the potential harm a failure can cause), occurrence (the likelihood of the failure happening), and detection (the probability of detecting the failure before it occurs). Add up these three and get the Risk Priority Number (RPN), which guides, the organization's actions related to the most dangerous risks. For example, in school laboratories, FMEA may have potential use in hazard identification of chemical waste that is not disposed of properly, equipment malfunctions, or accidental spills.

Some studies have shown that FMEA is effective in addressing environmental management issues. Silva et al. (2015) used FMECA for the yogurt production process, and all the failure modes were identified, from acidity testing to packing, which directly improved quality. Similarly, Azizi, et al. (2022) applied FMEA in chemical plant production aimed to show the versatility of this tool in identifying environmental risk factors and implementing prevention measures for their mitigation.

FMEA has been used in laboratory settings to evaluate the environmental risks associated with chemical use and waste generation. Erdil and Erbıyık (2023) applied FMEA in a flexible packaging production company to identify high-risk environmental aspects, such as energy consumption and gaseous emissions and recommended corrective actions. Interestingly, their work highlights that such an assessment may be just as applicable in industries and laboratories due to the power of FMEA.

2.3.1 Applications of FMEA and Its Advantages

Failure Mode and Effects Analysis (FMEA) is not solely used for risk assessment. According to Mendes and Ebner (2013), it is also applied to evaluate and establish plans to control newly established processes. This aids decision-making related to the introduction of new products or processes, with a focus on enhancing customer satisfaction. Moreover, FMEA is instrumental in analyzing failures in existing processes to improve quality. Publications demonstrate that the FMEA methodology has applications in various sectors, bringing substantial results, such as cost reduction, decreased environmental impacts, waste reduction, and better utilization of resources (Table 1). These outcomes benefit companies, employees, the environment, and society in general.

Table 1 - Synthesis of Studies on FMEA Applications

Citation	Application	Results	Benefits/Improvements
Maciel & Freitas (2014)	FMEA applied to a flexible packaging company	Identified critical points in production and office-related activities, focusing on energy consumption and waste generation.	External training and alternative technological solutions reduced energy consumption and improved environmental impact.
Silva et al. (2015)	FMEA applied to yogurt production in a small dairy plant	Identified risk priority number (RPN) for acidity tests and packaging process.	Preventive actions included training and equipment maintenance, improving the process's structure and ensuring product quality.
Pontes, et al. (2016)	FMEA applied to analyze environmental impacts in dental services	Identified 29 environmental risks, particularly in restoration procedures.	The tool allowed managers to outline practices for mitigating risks, resulting in improved environmental performance.
Casotti et al. (2017)	FMEA applied to the artisanal fishing industry	Addressed processing quality and public support issues in fish production chains.	Incentives were provided for processing quality improvements, and partnerships with public authorities were established.
Silva et al. (2017)	FMEA applied to a slaughterhouse	Identified 41 environmental aspects, focusing on waste from production and confinement activities.	Improved environmental planning and selective waste collection resulted from FMEA analysis.
Azizi, et al. (2022)	FMEA applied to health, safety, and environmental risk assessment in the chemical industry in Tehran	Identified 17 significant risks, with a focus on air and water pollution, soil contamination, and safety hazards	Improved risk prioritization and guidance for implementing preventive measures to reduce environmental and health risks in industrial settings.

2.4 Cleaner Production (CP)

Cleaner Production (CP) is an environmental management approach that aims to reduce waste and pollution by optimizing resource usage and increasing efficiency. According to Guedes, Simone, and Barata (2011), CP minimizes the consumption of raw materials, water, and energy in production processes while reducing waste generation. In laboratory settings, CP practices involve reducing hazardous chemicals, improving energy efficiency, and recycling materials whenever possible.

The CP is based on the concept of eco-efficiency, with an emphasis on waste prevention (i.e., reduction at source for ecological and economic reasons). CP strategies may include improved control over inventories, switching to less hazardous alternatives for laboratory chemicals, and purchasing energy-efficient equipment. CP with FMEA helps organizations identify critical points where they can implement some controls/mitigations that not only minimize risks but also contribute to sustainability.

Various studies have explored the benefits of CP in different industrial and academic settings. Oliveira et al. (2015) identified both the benefits and challenges of CP in four industrial companies in São Paulo, noting that while the environmental gains were significant, economic factors sometimes hindered full CP implementation.

Nara et al. (2015) showed how CP successfully applied it to a roto-molding process; overall costs and waste were significantly cut by eliminating cotton gloves in the manufacturing process. In the context of laboratory management, the improvement achieved by subjecting CP was found to have significantly enhanced environmental performance.

Santos, et al. (2020) pointed out that improving water and energy management and enhancing chemical waste management in a hospital enhance positive environmental impacts. That the laboratory was able to reduce the CP but was still able to produce high results in both research and teaching was a unique success.

2.4.1 Applications and Advantages of Cleaner Production

According to Guedes, Simone, and Barata (2011), the implementation of Cleaner Production (CP) in laboratories proposes changes in both technology and processes to reduce costs, minimize environmental impacts, and maintain research quality. The success of CP requires the commitment of all stakeholders, including management, technical staff, professors, students, and outsourced personnel. CP applications span various sectors, as illustrated in Table 2 of the original text, which highlights studies from different industries, demonstrating significant economic and environmental benefits (Guedes et al., 2011).

The implementation of Cleaner Production in various industries provides clear economic, environmental, and social benefits. Studies have shown significant cost savings, reduced environmental impact, and the potential for continuous improvement in processes. CP has proven effective across sectors, from dairy production to wastewater treatment, by promoting sustainable practices and compliance with environmental legislation Almeida (2021).

Table 2. Synthesis of Studies on Cleaner Production Applications

Citation	Application	Results	Benefits/Improvements
Oliveira et al. (2015)	Cleaner Production in industrial companies in São Paulo	Significant reduction in resource usage and waste generation	Economic gains through better management of production processes and environmental improvements.
Nara et al. (2015)	CP in rotomolding processes to reduce glove usage	Replaced simple cotton gloves with more durable material	78% reduction in glove costs, 68% reduction in waste generation, social and environmental improvements.
Silva et al. (2015)	P+L in a large-scale pig slaughterhouse	Focused on reducing water consumption in cleaning processes	Reduced water usage, production costs, and increased awareness of water conservation and recycling of production waste.
Silva & Silva (2017).	Cleaner Production in the red ceramic industry in Brazil	Analysis of waste and inefficiencies in production processes such as extrusion, drying, and firing	Identified significant environmental benefits from process optimization and suggested improvements in resource management, enhancing sustainability in red ceramic production.
Herzer, Robinson & Nunes (2017)	CP and Industrial Symbiosis in synthetic laminates	Reduced solid waste generation and facilitated the sale or exchange of waste materials to partner companies	95% projected reduction in waste disposal costs and environmental improvements through waste recycling.
Santos, Queiroz & Neto (2018)	CP in a dairy factory in Southern Bahia	Identified key environmental challenges with wastewater and solid waste from production	Cost savings from reduced raw material and waste treatment costs, improved environmental compliance, and more efficient resource utilization.
Leite & Neto (2018)	Economic evaluation of P+L in a wastewater treatment plant	Demonstrated monthly economic savings of approximately R$ 4,994 from an initial investment of R$ 4,560	Significant environmental and economic benefits from improved resource management, particularly in water conservation and compliance with local regulations.
Pena, Pinheiro, Costa & Teixeira (2021)	Cleaner Production as a competitive advantage in a sock factory	Evaluation of environmental, economic, and social aspects; suggested new sustainable actions	Significant cost savings, enhanced sustainability, and competitive advantage through waste reduction, energy efficiency, and improved production practices.

3. Methodology

This research uses case study procedures to assess the environmental aspects and impacts associated with the chemistry laboratories of the IHB in Coari, Amazonas. To achieve this, the research integrates two essential management tools: FMEA and Cleaner Production (CP). These tools were selected because of their opposite specializations; while the first is oriented toward risk evaluation, the second is best suited for environmental management. The methodology is structured in five phases: [1] The first step includes deciding and outlining the preliminary data to be collected from the particular laboratory; [2] Laboratory process mapping refers to developing and designing a principle map of the chosen laboratory; [3] FMEA application implies applying Failure Mode and Effects Analysis to the specific laboratory; [4] CP implementation recommendation includes recommendation and finding out the best strategies for the implementation of CP in the particular laboratory; [5] Lastly, report generation involves All these phases are intended to provide an orderly way of collecting information regarding the environment, analyzing risks, developing recommendations on how to deal with the perceived risks.

Phase 1: Preliminary Data Collection

The first and foremost important stage of the data collection was to collect the first information on the laboratories for children and their activities. This was achieved by direct observational assessment of the laboratory setting, a survey of the laboratory personnel, and documentation of activities undertaken in the laboratory, the utilization of chemicals, and the production of waste. At the same time, non-participant observation notes were taken on waste management disposal procedures, resource consumptions (water, energy), and safety measures being implemented.

Phase 2: Laboratory Process Mapping

The following phase was dedicated to the business analysis of all key chemistry laboratory processes. The chemical storage procedures, chemical use and disposal, energy use, and emissions at each phase of the laboratory activities were identified in terms of what was brought in and the resultant outputs in the form of waste and emissions. Assist with the lab process map completed this exercise to define the flow of material and chemicals that is a base for further FMEA. Evaluating the processes was critical to acknowledge which areas might experience a failure or risk shortly.

Phase 3: Application of FMEA

In this third phase of the study, the application of the FMEA tool is focused on discovering risks that may happen in the laboratories. This tool helped identify and assess Failure Modes (chemical leaks, poor waste disposal, equipment failure) in the environment and the lab. Each failure mode was evaluated using three criteria:

- consequence (hazardous to the environment or health)
- frequency (the chance of the failure occurring)
- exposure (the likelihood of identifying the failure before it generates harm)

The outcome of this analysis was the derivation of the Environmental Risk Index (ERI) for each of the identified failure modes. This enabled ranking risks in a bid to receive the highest potential environmental impact. The identified risks were then classified into four different categories: High, Medium High, Medium Lower, and, finally, low-level risks. Higher priority went to those with problematic environmental or health impacts and, therefore, concerning.

Phase 4: Cleaner Production Recommendations

As a result of the FMEA analysis, the fourth phase of the intervention was focused on identifying and recommending Cleaner Production (CP) strategies. While the management approach focuses on waste reduction and minimization at source, the CP approach focuses on the paramount waste minimization and reduced resources consumed. Measures were suggested, which included minimizing the use of toxic substances, increasing energy conservation, improving water saving, and recycling or utilization of wastes. The CP recommendations could be proposed based on actual observations of the situation in the IHB chemistry laboratories. The approaches to safety risk that would be implemented in the chemical laboratory based on the FMEA analysis are as follows: These safety strategies were developed to reduce the risks mentioned in this paper and increase the sustainability status of the chemical laboratory. Every recommendation reflected that there would be environmental gains and that the changes needed for these gains would also lead to cost savings for the institution.

Phase 5: Report Generation

The last stage of the methodology was producing a best-length report about the study result and the measures that can be taken into practice for enhancing the environmental management in the laboratories. This report was designed to contain explicit guidance on implementing the proposed WMS together with priority actions depending on the levels of risk determined. Further, the timeline for the implementation of the recommendations and the staff and management responsibility of a laboratory implementing the WMS were highlighted in the report.

3.1. Methodology Flowchart

The following flowchart illustrates the overall structure of the methodology used in this study, from the initial data collection to the final reporting stage (Figure 1):

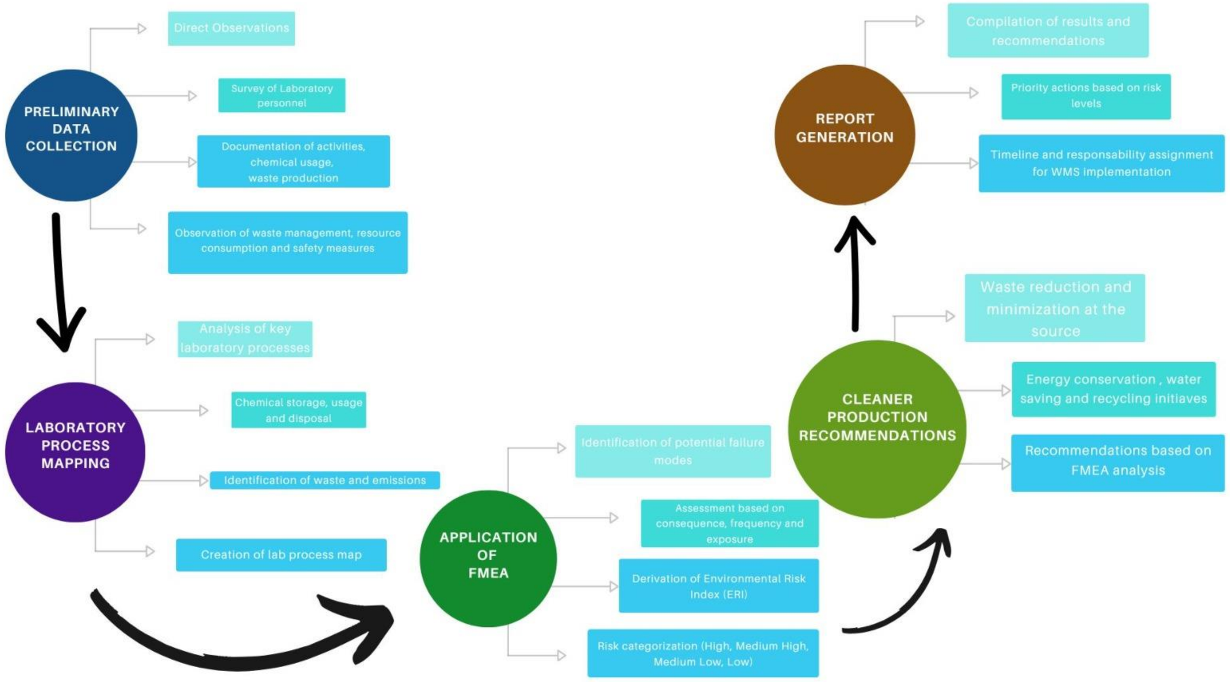

Figure 1 -Methodology Flowchart.

3.2. *Waste Management Systems*

A robust WMS is essential for institutions that generate significant amounts of waste, particularly hazardous waste, as part of their operations. According to Teixeira et al. (2012), a WMS should include waste segregation, collection, transportation, treatment, and final disposal procedures. These systems help ensure that hazardous waste is managed correctly to prevent environmental contamination and human health risks.

In educational institutions, the successful implementation of a WMS is contingent on the active involvement of all stakeholders—students, faculty, and staff. Couto (2010) underscores their crucial role in the waste management process, as it ensures compliance with best practices and promotes a sense of collective responsibility. This participatory approach not only raises awareness about the environmental risks associated with laboratory activities but also fosters a sense of ownership in minimizing waste generation.

Literature reveals that systematic tools, such as FMEA and CP, can be adopted for waste management / environmental sustainability in academic laboratories. Identification of environmental aspects and impacts and adaptation of measures to reduce risks or use resources can greatly help reduce the university's ecological footprint. The FMEA and CP approach applied to IHB laboratories might offer meaningful solutions that can be adopted with other best practices in managing waste through improved sustainability at educational institutions.

4. Results

This work is developed using Failure Mode and Effects Analysis (FMEA) and Cleaner Production (CP) in the chemistry laboratories at the Institute of Health and Biotechnology in Coari, Amazonas. These methodologies helped assess the environmental components and consequences related to the functions and processes in a laboratory. They were an excellent basis to look for vulnerabilities and recommend measures to minimize environmental contraventions. This section provides the assessment results of 21 out of the 67 analyzed processes, including assessing environmental risks and their prioritization and formulating related recommendations.

4.1 Identification of Environmental Aspects and Impacts

For laboratory practices, the initial phase in this study was to map all laboratory activities and assess the environmental aspects and impacts of those processes. These aspects were bundled into themes: waste generation, chemical emissions, and resource consumption. Processes were evaluated given each laboratory type closest to its counterparts as inputs (materials, chemicals, energy) and outputs. The new laboratory facility also supports research unit-based outreach efforts. This ensures the smooth functioning of laboratory-related work and its environmental implications.

4.1.1 The critical environmental aspects identified are as follows.

- *Chemical Waste*: It was generated from routine experiments as well teaching needed practical's and posed the greatest risk. The potential contamination of soil and water, if it is worst case scenario when non-disposed chemicals are condemned into nature, can lead to serious health hazards for laboratories staff as well as locals. This underscores the urgent need for proper waste disposal practices.
- Energy and Water Consumption: Energy and Water Consumption: Laboratory operations consume a considerable amount of energy (electricity and gas), particularly in cleaning and sterilization processes. These activities are necessary to ensure our comfort, safety, and hygiene, but they have environmental impacts from the use of non-renewable resources.
- Waste Disposal Practices: The inconsistency in waste disposal practices across various laboratories was shown to be consistent within the study. However, in some instances, chemical waste was blended wrongly with general rubbish, which can lead to more dangerous environmental effects.

4.1.2 Application of FMEA: Risk Identification and Prioritization

The laboratory processes systematically identified potential failure modes and their associated environmental impact using FMEA methodology. Each failure mode recognized was rated on three dimensions: severity (the magnitude of the consequence), occurrence (how frequently it will occur), and detection rate loss before it confronts injury. The Environmental Risk Index (ERI) was developed by aggregating these criteria, which provided a numerical value to prioritize the risks. The following key outcomes were noted and present in Table 3.

Table 3. Key Identified Risks and Priorities

Process	ERI (Risk Index)	Priority Level	Laboratory
Crystallization of compounds	567	II	General Chemistry
Oxygen and sulfur element practices	504	II	General Chemistry
Metal salts flame test	567	II	General Chemistry
Melting point determination	378	I	Organic Chemistry
Alcohol content determination in gasoline	432	I	Physical-Chemistry/Analytical Chemistry
Functional group characterization (aldehydes, etc.)	729	II	Physical-Chemistry/Analytical Chemistry

According to the Table 3, the highest priority was found in the synthesis of aspirin and the functional group tests in organic and analytical chemistry, with ERI values above 700, indicating urgent intervention requirements.

4.2 Summary of FMEA Results

The study identified 32 unique failure modes with different levels of risk from a total of the 21 processes it analyzed. Based on the ERI, these were divided into four priority levels, where the risk distribution is presented in Figure 2.

- **Priority I (High Risk):** Two failure modes were classified as priority I. One was detected with ERI values greater than 365. These were cases of hazardous substances not being adequately controlled, leading to their storage and disposal without due diligence. In the case of this class, these risks were deemed to be high since they could cause environmental contamination without well-established detection.
- **Priority II (Moderate Risk):** ERI values above 365; eight failure modes identified. Some involved the handling of hazardous chemicals in a rudimentary safety regime with holes around waste management and monitoring.
- **Priority III (Low Risk with Control):** Six failure modes fell into this category. These processes had ERI values below 365 but were already subject to adequate control measures, such as using personal protective equipment (PPE) and proper waste segregation.
- **Priority IV (Low Risk without Control):** The last 16 were Priority IV failure modes. These had ERIs below 365 but did not have adequate control measures. While their environmental footprint was minimal, there was still a lack of foresight and, therefore, room for improvement.

The high-risk failure modes, especially those in Priority I and II, were primarily related to hazardous waste management and chemical storage. These processes were considered very important and, if not intervened at that moment, would have caused considerable environmental harm.

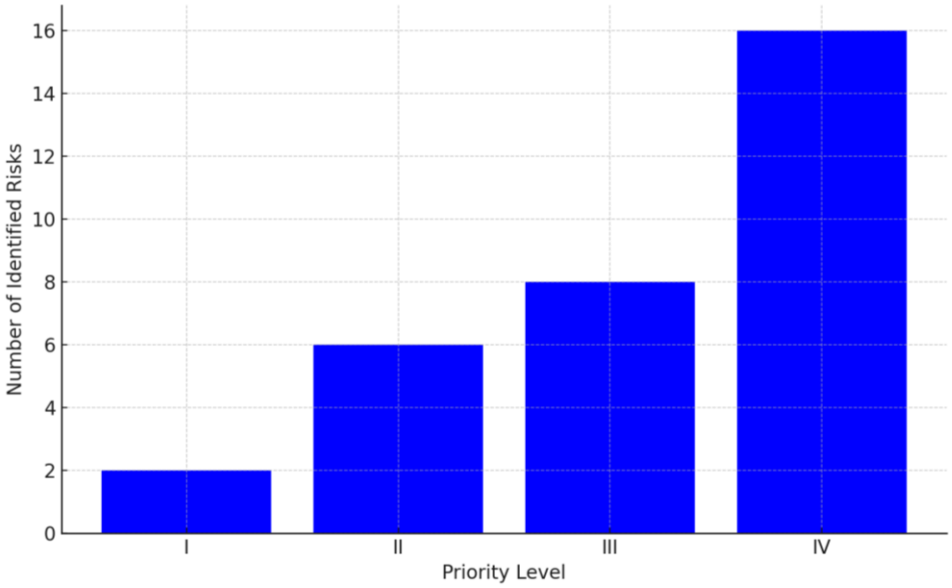

Figure 2 - Risk Distribution by Priority Level.

Key actions proposed based on the results of the FMEA included: 1. Establishing a designated secure area for chemical waste storage. 2. Introducing safer alternatives for hazardous reagents, such as replacing sodium hydroxide (NaOH) with sodium chloride (NaCl). 3. Installing biosafety equipment, such as showers and eyewash stations, to enhance safety compliance within the laboratories.

4.3 Recommendations Based on Cleaner Production Principles

From the FMEA, a crucial tool in identifying potential risks, Cleaner Production (CP) methods were suggested to minimize the risks and make the lab operations more sustainable. The CP recommendations aimed to minimize waste generation, optimize resource use, and reduce the environmental impact of the laboratory activities.

4.3.1 Key CP Recommendations

1. *Improved Waste Segregation and Disposal:* One of the leading suggestions was to improve garbage separation. This included sorting contaminated chemical waste from regular lab trash and properly disposing of all hazardous materials according to state and federal regulations. Additionally, waste recycling and treatment options were recommended where feasible.
2. *Reduction in Chemical Use:* According to the study, it should use as few hazardous chemicals in its experiments as possible to produce the least hazardous waste. This action could be done by replacing more hazardous chemicals with less toxic substitutes and conducting experiments on a microscale level so that fewer chemicals are used.
3. *Energy and Water Efficiency:* The study found room for improvement in laboratory operations' energy and water conservation. Suggestions ranged from using energy-saving machinery to making the A/C systems run more efficiently to using water-conserving techniques for cleaning and sterilization.
4. *Training and Awareness Programs:* One of the key recommendations from the CP was the development of comprehensive training programs for the lab personnel, particularly the students. These programs are designed to enhance their understanding of environmental risks and best practices in waste management, chemical handling, and resource conservation, thereby fostering a culture of environmental responsibility.
5. *Enhanced Monitoring and Reporting:* The report suggests the implementation of an Environmental Management System (EMS) to monitor the laboratory's environmental performance. This system would track key metrics such as garbage output, energy and water consumption, and compliance with environmental laws. By providing continuous feedback, the EMS would enable the identification of problem areas and ensure ongoing adherence to environmental standards.

4.4 Impact of Implementing the Recommendations

All these recommendations should be implemented and will significantly improve the environmental efficiency of the IHB laboratories. Lean labs can soften their environmental harm by using the risk factors discovered in the FMEA and applying cleaner production methods without compromising safety and operational capacity. They are being developed with the active participation of people in this process, which is critical to their success.

Thus, if waste disposal is separated correctly so as not to contaminate the local water supply and use fewer hazardous chemicals so as not to produce as much hazardous waste, energy-saving machines, and water-saving technologies will also be used to cut down on the number of resources this laboratory consumes and, therefore, contribute to the long-term sustainability of these goals.

4.5 Monitoring and Continuous Improvement

The kaizen process will also need to be developed for these recommended countermeasures to continue to be effective in the long run. Now, this is an ongoing process that involves constantly monitoring environmental performance, updating risk assessments, and reviewing the effectiveness of the controls, so it will be up to us to keep that commitment and stay diligent. Nevertheless, with this kind of initiative, we not only follow environmental laws, but we can make a dent in our impression of the environment.

4.6 Summary of Key Findings

- *Environmental Risks:* The study identified 32 environmental risks associated with the laboratory processes, categorized into four priority levels based on the Environmental Risk Index.
- *FMEA Application:* The FMEA methodology provided a systematic approach for identifying and prioritizing environmental risks, with the highest risks associated with hazardous waste management and chemical storage.
- *CP Recommendations:* The Cleaner Production strategies that this study suggested included better waste separation, lesser use of chemicals, more efficient use of energy and water and finally, the training of staff and students.

- *Expected Impact:* If these suggestions are followed, the laboratories' environmental impact will be drastically reduced, resource efficiency will be improved, and environmental laws will be obeyed.

5. Conclusion

The present study successfully applied the methodologies of Failure Mode and Effects Analysis (FMEA) and Cleaner Production (CP) to identify, evaluate, and mitigate environmental risks in the chemistry laboratories of the IHB in Coari, Amazonas. Through a systematic assessment of 21 key laboratory processes, 32 environmental risks were identified and categorized into four priority levels based on their Environmental Risk Index (ERI). The findings highlighted the critical areas where immediate intervention is required, particularly in managing hazardous waste and chemical storage.

FMEA proved effective in prioritizing risks and providing a structured approach for addressing potential environmental failures. The most critical risks—classified as Priority I and II—were related to improper chemical waste disposal and the lack of sufficient control measures. The study demonstrated that a targeted approach to addressing these risks could significantly reduce the environmental impacts of laboratory activities.

Cleaner Production strategies were then proposed to address the identified risks. These recommendations focused on waste reduction, resource optimization, and promoting sustainability in laboratory operations. Key measures included improving waste segregation practices, reducing hazardous chemicals, increasing energy and water efficiency, and developing training programs for laboratory personnel. Once implemented, these measures are expected to not only enhance the sustainability of the IHB laboratories but also ensure compliance with environmental regulations and improve safety for students and staff.

This study's objectives were achieved through a comprehensive analysis of the laboratory processes and the identification of specific areas for improvement. The combination of FMEA and CP methodologies provided a robust framework for understanding the environmental risks and proposing practical solutions. The recommendations presented in this study serve as a foundation for developing a tailored WMS that aligns with the realities of the IHB laboratories, fostering a safer, more sustainable academic environment.

In conclusion, the adoption of the proposed measures will contribute to reducing environmental impacts, complying with regulatory standards, and ensuring the long-term sustainability of the IHB laboratories. These findings also provide valuable insights for other academic institutions facing similar challenges, demonstrating the importance of integrating environmental management practices into the daily operations of research and teaching laboratories.

6. Limitations and Further Recommendations

The study's implementation was restricted due to pandemic-related limitations, preventing a full re-application of the FMEA form. However, it provided a comprehensive baseline for IHB management to build upon. Follow-up actions, including continuous monitoring and further analysis of corrective actions' effectiveness, were recommended to ensure long-term sustainability.

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