Guidelines proposal for a corrosion management model of the craft brewing industry in Bogotá

Propuesta de lineamientos para un modelo de gestión de la corrosión en la industria cervecera artesanal en Bogotá D.C.

Proposta de alinhamentos para um modelo de gerenciamento de corrosão na indústria de cerveja artesanal em Bogotá D.C.

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Abstract

Introduction: Supported by Distrital Francisco José de Caldas University, this article presents a study on the guidelines for a corrosion management model for the craft brewing industry in Bogotá D.C., conducted in 2024 and 2025.

Problem: Corrosion is a phenomenon that can lead to economic and material losses, health problems, and environmental issues caused by the deterioration of metallic equipment [1], [2], [3].

Objective: To propose guidelines for a corrosion management model in craft breweries that align with national and international standards.

Methodology: A literature review was conducted on the factors that promote corrosion and the measures that minimize its economic and productive impact. This review took into account the characteristics identified during visits to craft breweries.

Results: Guidelines were established for a corrosion management model with a cyclical structure that begins by identifying requirements and potential causes of corrosion, thereby developing a policy aligned with other management systems to foster continuous improvement.

Conclusion: To make effective managerial decisions in the brewing industry, it is important to manage corrosion and to prevent and control the phenomenon in the face of economic and productive impacts.

Originality: Fieldwork and theoretical analyses of corrosion, along with their integration into an organizational management system, offer an innovative approach to the brewing industry.

Limitations: The proposed guidelines for a corrosion management model have not yet been implemented in the craft brewing industry.

Keywords: Corrosion, craft beer, management model, maintenance and control.

Resumen

Introducción: Este artículo, apoyado por la Universidad Distrital Francisco José de Caldas, presenta una investigación sobre los lineamientos de un modelo de gestión de la corrosión en cervecerías artesanales de Bogotá D.C., realizada en 2024 y 2025.

Problema: La corrosión es un fenómeno vinculado a pérdidas económicas y de materiales, afecciones de salud y problemáticas ambientales causadas por el deterioro de equipos metálicos [1], [2], [3].

Objetivo: Proponer lineamientos para un modelo de gestión de la corrosión en las cervecerías artesanales que esté alineado con estándares nacionales e internacionales.

Metodología: Se realizó una revisión bibliográfica sobre los factores que propician la corrosión y los pilares que minimizan su impacto económico y productivo, teniendo en cuenta las características identificadas en las visitas a las cervecerías artesanales.

Resultados: Se establecieron lineamientos para un modelo de gestión de la corrosión con una estructura cíclica que inicia identificando los requerimientos y posibles causas de corrosión, para así construir una política alineada con los demás sistemas de gestión que propicie la mejora continua.

Conclusiones: Para una adecuada toma de decisiones gerenciales en la industria cervecera, la gestión de la corrosión promueve estrategias para prevenir y controlar el fenómeno ante las afectaciones económicas y productivas.

Originalidad: El trabajo de campo y los análisis teóricos de la corrosión, junto con su integración en un sistema de gestión organizacional, aportan una propuesta innovadora para la industria cervecera.

Limitaciones: La propuesta de lineamientos para un modelo de gestión de la corrosión no tuvo alcance de implementación en la industria cervecera artesanal.

Palabras clave: Corrosión, cerveza artesanal, modelo de gestión, mantenimiento y control.

Resumo

Introdução: Este artigo, com o apoio da Universidade Distrital Francisco José de Caldas, apresenta uma pesquisa sobre as diretrizes para um modelo de gestão da corrosão em cervejarias artesanais de Bogotá, D.C., realizada em 2024 e 2025.

Problema: A corrosão é um fenômeno associado a perdas econômicas e materiais, problemas de saúde e questões ambientais causadas pela deterioração de equipamentos metálicos [1], [2], [3].

Objetivo: Propor diretrizes para um modelo de gestão da corrosão em cervejarias artesanais, alinhado com as normas nacionais e internacionais.

Metodologia: Foi realizada uma revisão bibliográfica sobre os fatores que promovem a corrosão e os principais elementos que minimizam seu impacto econômico e produtivo, levando em consideração as características identificadas durante as visitas às cervejarias artesanais.

Resultados: Foram estabelecidas diretrizes para um modelo de gestão da corrosão com estrutura cíclica, que se inicia pela identificação das necessidades e das causas potenciais da corrosão, construindo, assim, uma política alinhada a outros sistemas de gestão que fomente a melhoria contínua.

Conclusões: Para uma tomada de decisão gerencial sólida na indústria cervejeira, o gerenciamento da corrosão promove estratégias para prevenir e controlar o fenômeno e mitigar seus impactos econômicos e de produção.

Originalidade: O trabalho de campo e as análises teóricas da corrosão, juntamente com sua integração em um sistema de gestão organizacional, fornecem uma proposta inovadora para a indústria cervejeira.

Limitações: As diretrizes propostas para um modelo de gerenciamento da corrosão não foram implementadas na indústria de cerveja artesanal.

Palavras-chave: Corrosão, cerveja artesanal, modelo de gestão, manutenção e controle.

1. INTRODUCTION

Beer is a product that has been known since ancient times and spread from Mesopotamia to the Americas. It is part of cultures around the world and influences social and economic factors [4]. Over the past two decades, Colombia's beer market has grown, as evidenced by a per capita consumption of 49.9 liters in 2022 compared to 46.5 liters in 2021, establishing it as the second-largest beer consumer in South America after Brazil [5], [6]. In response to changing consumer preferences, the beer industry is focusing on developing new flavors, offering greater variety, and adopting advanced technologies and equipment for production and distribution, establishing craft breweries as a source of innovation [7], [8]. With more than 250 micro-enterprises in 2023, this segment represented 1% of the market and projects an annual growth

rate of 5.5% over the next eight years [9], [10]. Specifically, in Bogotá D.C., it accounted for 44% of total national sales [5], [6].

Additionally, with respect to technical and commercial aspects of this industry, new studies have shown an increase in publications related to craft beer. Research aimed at determining consumer preferences [11], different formulations and/or processes [7], [12], analysis of the impact on the physicochemical characteristics and flavor of craft beer, modifications in raw materials such as cereals and yeasts, or the integration of processes such as stirred freeze concentration [8], [13], as well as inquiries into the effects of conditions such as pH, alcohol concentration, or storage temperature that facilitate or inhibit the growth of pathogens, among many others [14].

Although less abundant, there is also research related to the effects of corrosion on metallic materials such as pipes, fittings, production tanks, storage tanks, or packaging components used in the manufacturing, storage, and packaging processes in the brewing industry [15], [16], [17], [18]. Several authors recognize relevant technical aspects that seek to prevent corrosion not only to avoid material deterioration and reduce production time losses, but also to prevent contamination of products in contact with these materials, thereby ensuring their quality [19]. Additionally, from an economic perspective, it has been determined that corrosion is one of the causes of multimillion-dollar losses, equivalent to 3.4% of the world gross domestic product (GDP) [20].

Corrosion is an electrochemical REDOX reaction centered on the oxidation of metals, which leads to chemical, physical, and aesthetic modifications, from deterioration to the loss of metallic material due to interaction with oxidizing agents present in the surrounding environment. In production processes such as beer manufacturing, which has an average pH of 4.2, this reaction can occur due to multiple factors, such as contaminants from corrosion products of metallic pipe materials; the use of unsuitable processing equipment materials, such as AISI 304, which is not resistant to pitting corrosion [4]; or reactions with raw materials or substances required for manufacturing or cleaning infrastructure and machinery. For example, water requiring high-temperature conditions or tank components can react with substances present during beer fermentation [16]. In addition to the chemical nature of products and their concentrations, environmental factors such as humidity, air quality, solar radiation, and pollution can also influence the reaction [15], [21], [22].

Worldwide, the significant negative impacts of corrosion in different industries are evident. Problems include modifications to the physical and mechanical properties of materials that lead to an increase in the consumption of raw materials and energy, the generation of greater volumes of pollutants and waste, and the significant reduction of the useful and structural life of equipment and machinery [23], [24], [25]. These

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impacts cause economic, environmental, logistical, and administrative difficulties that prompt organizations to prioritize preventive actions and periodic control, including staff training to efficiently counteract the phenomenon [26], [27].

According to studies conducted by the National Association of Corrosion Engineers (NACE International) in 2013, it is estimated that the world lost $2.5 trillion in one year due to corrosion-related problems [20], a silent cause of multiple incidents and a driving force behind the failure of systems and infrastructure. This includes accidents related to leaks in substance-transport pipes, generating material losses and explosions; the weakening of metal-supported structures, leading to collapse; contamination of products in process due to the detachment of particles [28], [29], [30]; and damage caused to industries when they do not have the capacity to cover the resulting costs [26], [31]. In the food industry, such situations can lead to contamination of various kinds, causing human and environmental losses, long-term health effects, and an increase in disease outbreaks [30], [32], as it indirectly affects safety in the production process [33].

Information on corrosion maintenance costs in production industries is scarce, since, at present, administrative accounting systems consider expenses related to corrosion globally within common maintenance processes. This prevents the real impact generated by low control of this phenomenon in production processes from being clearly evidenced. As a result, industries incur both preventive and corrective maintenance actions, the latter being more costly, as parts must be removed or replaced and/or production must be halted while existing defects are repaired [20]. It has been estimated that, on average, 5% of annual maintenance costs in the food industry are directly related to corrosion [34].

To address this problem from the industrial point of view, there are proposals focused on developing management systems. Authors such as [35] define the management system as a set of interrelated elements and activities that employ objectives and policies to direct and control the industry in order to achieve established goals. This association promotes the implementation of a corrosion management system, which first requires identifying the different variables that allow measuring the costs derived specifically from corrosion, in order to determine the savings generated by its mitigation and utility [20], [22].

Since transversal management systems are very robust and their application, in many cases, is not feasible for small industries such as craft beer production, it is necessary to develop studies focused on proposing corrosion management systems integrated into general quality management and continuous improvement systems in craft industries, which should be included within the framework of production policies.

1.1 General quality management systems in food and beverage industries

In quality management systems, the link between planning, organization, direction, coordination, and control of different processes is transformed according to industry needs, seeking a real and as accurate as possible representation of the environment to adapt a management model that meets the proposed objectives [36]. Implementation of quality and complementary management systems is fundamental for food and beverage industries, as it allows processes to be executed adequately, guaranteeing safety and innocuousness in consumer products [37], [38]. On the other hand, integral and transversal management systems are not only focused on quality but also include environmental management, occupational health and safety, and food safety. For the normative implementation of an integrated management system, it is necessary to include several standards such as those of the International Organization for Standardization (ISO): standards aimed at quality production processes (ISO 9001), environmental management systems (ISO 14001), occupational health and safety management systems (ISO 45000), and standards to ensure safe processes in the food industry (ISO 22000), as well as standards for Hazard Analysis and Critical Control Points such as HACCP, which are related and developed based on similar quality objectives [39].

Throughout the years, it is evident that in the Colombian food industry, legal requirements for companies in terms of quality management systems have increased, adapting to international standards and reflected in the Colombian Technical Standards (NTC) [38], [40], mainly adopting ISO 9001 [41], ISO 22000 [39], ISO 14001, ISO 45000 [35], and HACCP. The latter is promoted as a surveillance tool for food factories in Colombia by Decree 060 of 2002 [42], which also regulates its certification process [33].

Likewise, for craft brewing industries in Colombia, the implementation of specific standards that complement the general regulations in the food industry is considered. These standards regulate the production of alcoholic beverages and specifically beer, with respect to brewing methods and the determination of contaminants in the final product [40], [43]. They are governed by the National Institute of Food and Drug Surveillance (INVIMA), which establishes the minimum sanitary requirements in force for the creation, manufacture, and distribution of products [44]. Among these requirements is the use of stainless steel in production equipment, making it the most common material in the food and pharmaceutical industries [45].

The integrity and transversality of management systems in industries allow companies to align all their areas in pursuit of quality objectives oriented toward

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continuous improvement. Therefore, the implementation of the corrosion management model must be structured as part of the management system used in each industry.

1.2 General aspects of craft beer production

The production of craft beers in small and medium-sized enterprises (SMEs) differs very little from large-scale industrial production, as they use the same four main raw materials (water, yeast, malt, and hops), adding some additives that enhance the characteristic flavors of craft beers. During the process, the same unitary production operations are used: clarification, mashing, filtration, boiling, fermentation, purification, packaging, storage, and distribution, as shown in Fig. 1 [46], [47]. Differences arise in the production equipment, since in some cases the craft industry uses containers made of polymeric materials, while metallic equipment is necessary for stages that require heating [48].

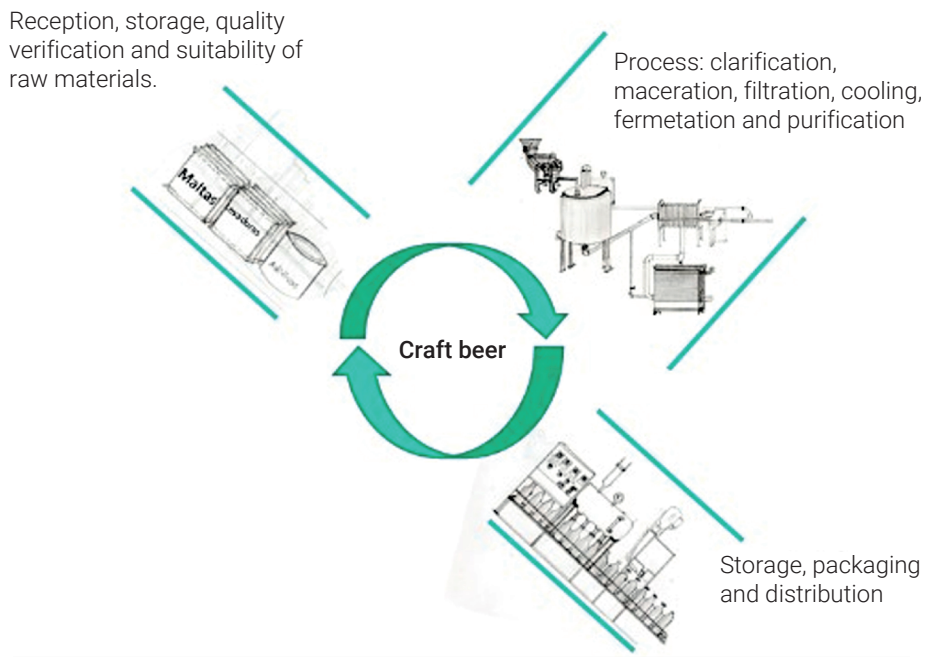

Figure 1. Diagram of the craft beer production process.
Source: Original work adapted from [49], [50].

Major industries have developed strategies or methodologies to counteract the problems generated by corrosion before it appears, since identifying the causes is

complex. These causes are not usually differentiated when general maintenance is performed on machinery, and they affect both the product and standard processes, making it difficult to disaggregate the real specific costs associated with this phenomenon. However, small and medium-sized craft breweries have not implemented such strategies, as they have not established a specific corrosion management system that considers their needs and characteristics.

1.3 Corrosion management models

Traditional corrosion management approaches for production industries are based on corrective maintenance systems characterized by interventions after damage has occurred. Preventive corrosion systems are based on technical data that contribute to inhibiting corrosion catalytic factors, supported by studies on possible functional coatings or other control methods [51], [52]. Prediction can also be an approach to integrate corrosion management into production management systems [53]. However, it is not easy to implement preventive or predictive maintenance systems due to insufficient technical information for each type of industry.

NACE International has proposed standard pillars of the corrosion management system for implementing a model according to the characteristics of each industry, as a response to the problems caused by corrosion that have generated damage to the useful life of fixed assets, increased maintenance costs and unexpected budget expenses, and impacts associated with the health of human resources and the environment [20], [54]. These pillars serve as the basis for the present proposal.

2. METHODOLOGY

To establish the management guidelines, a systematic review was conducted to support the understanding of the basic aspects of management systems, which are mentioned in the introduction of this document, and which lead to the establishment of guidelines for the corrosion management model for craft brewing industries in Bogotá D.C. Additionally, to achieve a relevant approach to this craft industry, visits to companies are proposed to learn about their processes and prepare a survey to collect relevant information that allows establishing several variables of the management model.

A search was conducted online and in different databases and business information sources ([55], [56]), identifying several companies engaged in the manufacture and distribution of this type of beer. These companies were tabulated with

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basic contact information. The selection criteria for the analysis included small and medium-sized craft breweries (with fewer than 10 permanent employees) that offered a variety of beer types and flavors, had different production volumes, owned their production equipment (not subcontracted to specialized companies), and had obtained or were in the process of obtaining health registration with INVIMA.

The main objective of the visit is to obtain information classified into two sections: the first to identify general and specific aspects characterizing the industry, and the second to understand how different quality management systems and their related pillars are implemented. For the first section, it was relevant to collect information regarding the specifications of the machinery used in the industry, such as the material of construction, time of use, useful life, maximum capacity, among others, as well as the approach of the maintenance area and the type of inputs used in cleaning. The second section includes questions about the norms and standards used in the transversal management systems in place, corrosion problems presented, and the economic losses or evaluated impacts derived from them.

Given the growing relevance of corrosion management, implementing a specialized model in industries that may present this phenomenon is important. This proposal focuses on the craft brewing industry in Bogotá D.C. and takes as a reference the initial structure developed by NACE International, a leader in issues related to corrosion, its control, and prevention. Taking this system into account, the management model is structured according to the aspects that characterize each industry and its specific size. Therefore, several companies in the brewing sector with similar conditions—such as craft manufacturing, small-scale production, stainless steel machinery, among others—are studied to analyze the main aspects related to corrosion, considering specific problems, economic losses, maintenance and cleaning processes, and their approach to continuous improvement.

3. RESULTS

From online research, a total of 11 craft breweries that met the selection criteria were found through an online search (Table 1). Each of these companies was contacted, and 45.45% of the total sample responded positively to a request to visit their production facilities. Therefore, the information used to propose the guidelines is based on the data and results of the representative sample of five (5) companies that agreed to the visit and responded to the survey.

Table 1. Craft brewery in Bogotá D.C.

Craft Brewery Name	Beer Types	Number of types of beer	Number of employees
Craft brewery A	American stout IPA Summer Ale American Pale Ale	7	6
Craft brewery B	Golden Ale Strong Ale IPA Pumpkin Ale American Pale Ale	10	10
Craft brewery C	American Amber Ale IPA Tripel belga Imperial stout	4	3
Craft brewery D	Scottish Ale Golden Ale Blonde Ale	4	2
Craft brewery E	Blonde Ale Imperial stout American Pale Ale	6	5
Craft brewery F	WitBier Amber Ale IPA Strong Ale	6	5
Craft brewery G	Amber Ale Blonde Imperial stout IPA English porter WitBier	8	9
Craft brewery H	Wheat Ale Blonde Ale Amber Ale American Pale Ale Stout Rosé	6	4
Craft brewery I	Porter Golden Ale Stout American Pale Ale WitBier	7	6

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Craft Brewery Name	Beer Types	Number of types of beer	Number of employees
Craft brewery J	Blonde IPA Lager	3	2
Craft brewery K	Double IPA Alcohol free American Pale Ale English strong Ale IPA Porter Lager Stout WitBier	22	10

Source: [55], [56].

3.1 Basic information on craft breweries in Bogotá D.C.

By conducting the surveys in each craft brewery in Bogotá D.C., qualitative and quantitative data were obtained that allowed identifying strengths and opportunities for improvement in the production process, using this information as input for defining the guidelines of the corrosion management model. Given the focus of the model, information related to machinery and its maintenance, as well as production and cleaning processes, is highlighted. It was found that the craft beer production process in Bogotá and the machinery used coincide with the global standards shown in Figure 1 of the previous section. As shown in Figure 2, the time of use of the machinery in the industries visited is very short due to their recent creation dates. Equipment manufacturers suggest that the useful life of the equipment ranges between 10 and 15 years (Figure 3), and because of the short time in operation, no significant deterioration or evidence of corrosion is observed. Considering the useful life and current production capacities (Figure 4), it is estimated that these industries should perform maintenance or replace equipment after producing between 129,600 and 144,000 liters of craft beer (Figure 5).

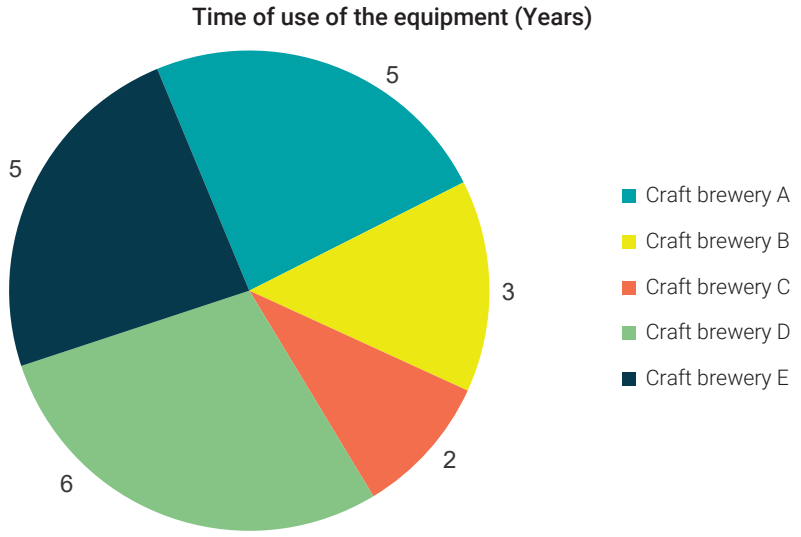

Figure 2. Time of use of the equipment in years.
Source: own work

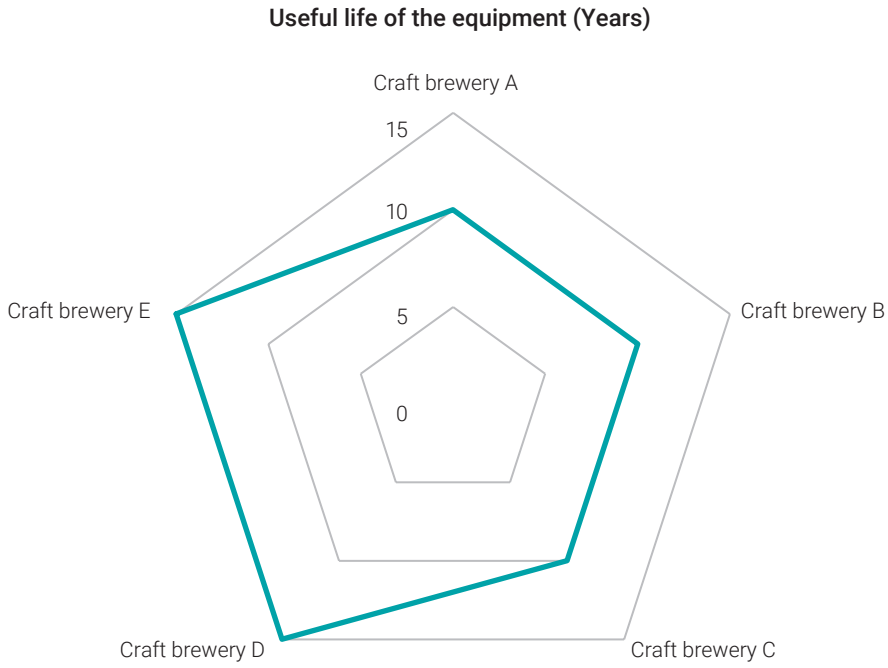

Figure 3. Estimated useful life of equipment in years.
Source: own work

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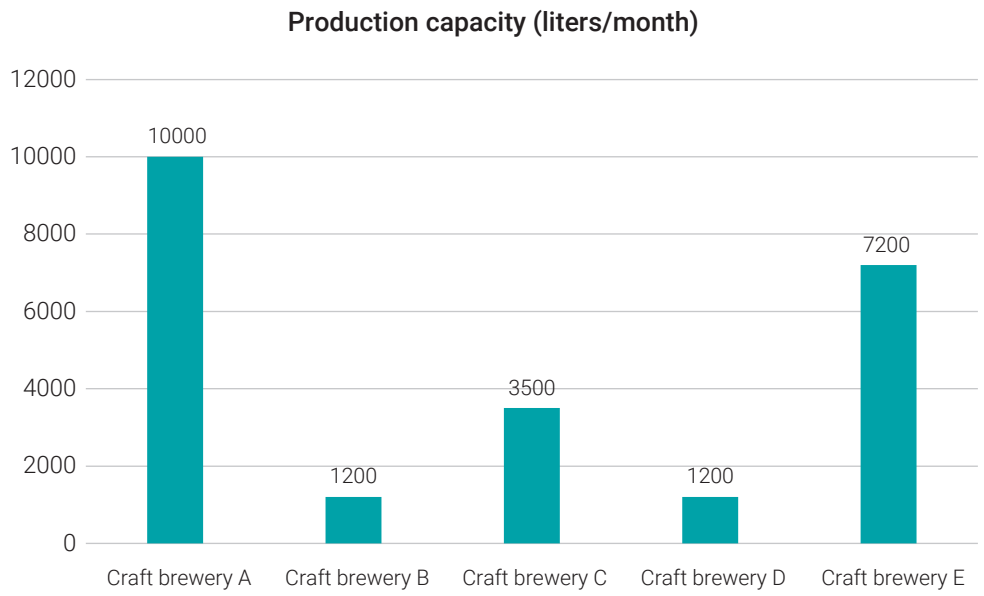

Figure 4. Craft beer production capacity in liters per month.
Source: own work

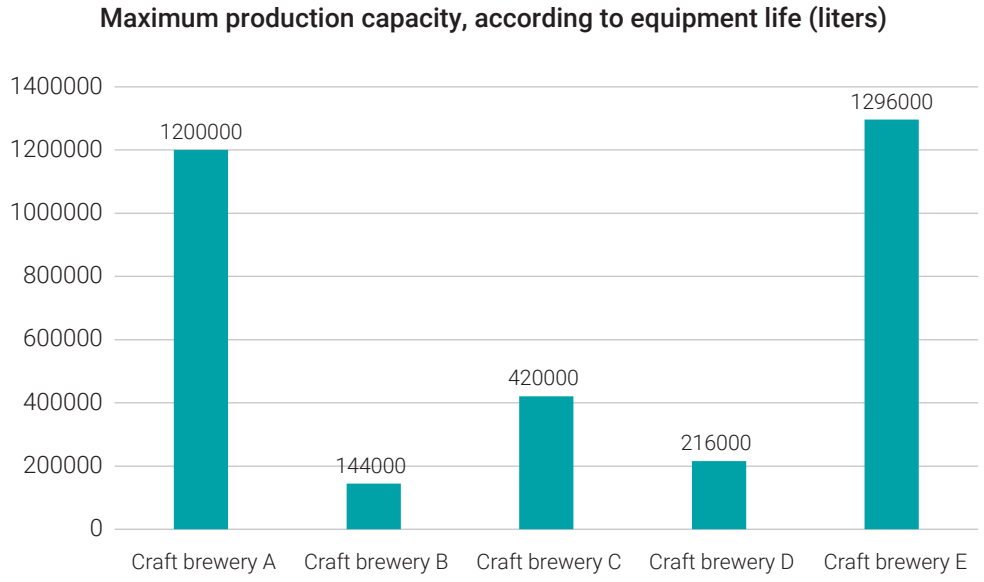

Figure 5. Maximum production capacity, according to useful life of equipment.
Source: own work

4. PROPOSAL AND DISCUSSION

4.1 Pillars of a corrosion management system

NACE International identifies several pillars for a corrosion management system. A total of seven pillars are used as elements to propose the guidelines for the corrosion management model incorporated into the quality system for the craft beer production industries in Bogotá D.C., as shown in Figure 6.

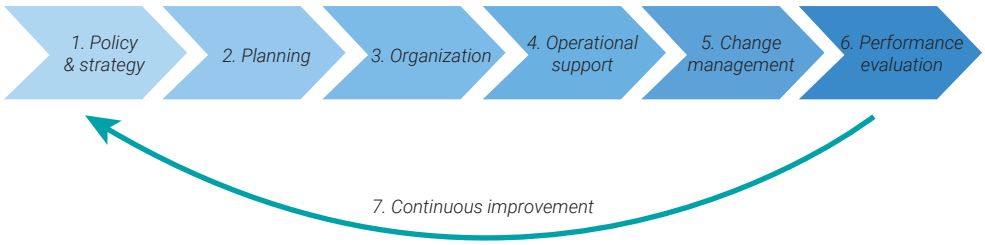

Figure 6. Corrosion management system.
Source: own work adapted from [54].

The most important aspects of each pillar are described below:

1. Policy & strategy: The organization should establish strategies for creating a corrosion policy aligned with the corporate purpose and the standards of national and international governmental entities.
2. Planning: To ensure synergy across all areas of the organization that may be directly or indirectly affected by corrosion, plans should be created focusing on risk and resource identification, communication management, and differentiation of roles and responsibilities, as well as integration with general quality management systems.
3. Organization: For proper implementation of the model, specialized corrosion management representatives are required to facilitate the analysis of improvement opportunities and promote corrosion awareness within the organization.
4. Operational support: This guideline, linked to the previous one, establishes the interaction of human and economic resources required for corrosion management.

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5. Change management: As the model is integrated into periodic operations, this item validates its functionality and analyzes possible modifications to comply with defined standards.
6. Performance evaluation: Measures of performance must be structured by defining their monitoring, analysis, and calculation frequency to compare the results obtained with the proposed goals.
7. Continuous improvement: Seeks to confirm the relevance and benefits obtained with the implementation of the model in the company, making use of the Deming cycle (PHVA) [54], [57].

4.2 Guidelines for the corrosion management model

Based on the seven pillars, it is proposed to integrate the results obtained during the visits to the different craft beer–producing companies in Bogotá D.C., and thus construct a proposal in which the dynamics of these companies are analyzed and, through their development and growth, adjust the guidelines for a corrosion management model for the different areas in an efficient and transversal manner. It is relevant to review the internal and external conditions and requirements in the production of this type of beer in Colombia, such as the types of alloys used in the machinery, the composition of raw materials [4], cleaning inputs, phases of the production process, and national and international standards or policies related to corrosion management, which will be interpreted considering the product supply chain. Likewise, integration with the general management system in place should be structured, creating specific plans for each area, as mentioned by the authors [36], [37], [38], guaranteeing synergy in the pursuit of corrosion control and prevention according to industry needs.

To comply with the control conditions established by the national policy of the National Institute of Food and Drug Surveillance of Colombia [44], some general process conditions are defined for the different stages of production in operating companies, such as the breweries visited. Among the requirements imposed by this institution are the use of stainless steel, airtight rooms, and other measures focused on guaranteeing food safety to avoid contamination throughout the production process. However, they do not consider the possible chemical reactions of raw materials and inputs when in contact with equipment, nor the environmental conditions that can cause corrosion.

Currently, given that these craft breweries have a high level of production, it is necessary to consider the following aspects: those that are in the initial stage and whose equipment is within the useful-life interval have already experienced problems

related to corrosion, such as rusting of drainage grids and liquid transport pumps, or damage to brewing train taps due to material loss. They do not give this issue the importance it deserves because it has not significantly affected their production times or batches, nor the long-term useful life of the equipment. For this reason, they have not implemented specific corrosion management policies aligned with maintenance and purchasing plans or with pre- and post-production cleaning schedules, among others.

Due to the size of craft breweries in Bogotá D.C., production, maintenance, and budgetary processes may be more affected when corrosion problems occur, as there is no alternative equipment to replace production while corrective maintenance is performed, resulting in a higher probability of increased maintenance costs and downtime [58]. Furthermore, in small production facilities, there may be a risk that immediate corrective repairs are carried out without stopping production, which may promote contamination of the product in process or the finished product through chemical reactions between the corroded metal and components of the raw material, cleaning agents, or production residues.

For this reason, the formulation of organizational maintenance plans focused on the prevention, control, and monitoring of corrosion should become more important in breweries, as it contributes to reducing associated risks and possible future failures [59]. Given the usual distribution of machinery in plants, maintenance currently tends to focus on corrective maintenance performed by specialized suppliers for each piece of equipment, with the exception of low-complexity repairs carried out by the operators themselves. This approach can become a shortcoming and, although it is impossible to avoid corrective maintenance altogether, anticipatory actions must prevail to avoid higher corrosion-related costs [26]. This requires drawing up a periodic plan that takes into account the life sheet of each piece of equipment and its accessories and the responsible experts, highlighting production times, downtimes, and use times of each batch, and, when appropriate, relying on a methodology for stocking spare parts to avoid unexpected delays. In addition, a technical process of passivation and anticorrosive neutralization should be carried out on metal parts before their first use, as basic protection against this phenomenon.

Similarly, the structuring of cleaning programs for craft breweries makes it possible to consider the useful life of the equipment and the quality of the finished product. These programs include all necessary cleaning phases, based on national or international standards such as ISO 13027: Hygiene and Sanitation Standard, developed for food production industries [60], and define the pre- and post-operational sanitization steps. These steps consist of removing residues from previous production, washing and general disinfection of equipment using specialized products, cleaning storage

containers, and performing manual inspections before the next batch is produced. For proper implementation, those in charge of the process must be trained and certified in the handling of chemicals and other inputs, since each of them has characteristics—such as food-grade use, reduced reactivity with metals, neutral pH compositions, biodegradability, among others—that make them suitable or unsuitable for certain phases [61]. Field observations revealed that the most commonly used cleaning products are diluted phosphoric acid (disinfectant to eliminate possible microorganisms), Star San (rinse and final foam), peracetic acid (mycobacterial disinfectant), alkaline detergent (removes organic waste), and caustic soda (used to dissolve fats and oils). Additionally, the CIP (Cleaning in Place) method is implemented for equipment with pipes, since plant installations are fixed and immobile.

The search for synergy among the different areas in breweries, as well as the structuring and implementation of the corrosion management model, requires interaction with all personnel, both operational and administrative. Success and the achievement of benefits—such as reduced maintenance costs and extended equipment life—are attained through adequate knowledge of the process, assertive communication, and the distribution of responsibilities within a scheme of clearly defined roles, complemented by periodic training on topics related to corrosion management and control [26].

Based on the visits conducted, it can be observed that most craft breweries in Bogotá D.C. are microenterprises, with a maximum of 10 full-time employees sharing multiple responsibilities. Although the limited number of employees may pose an obstacle to the development of the model, it is important to allocate, from the outset, economic and time resources that include specialized external advice to define new functions; detail and analyze situations related to corrosion; consider basic characteristics of equipment and plant layout; and review components of raw materials and inputs, among others. These actions help establish prevention and control plans that ensure understanding and adaptation of the model.

On the basis of the analyses carried out and the dynamics identified in the artisanal breweries of Bogotá, the reasons for the lack of consideration for the implementation of a corrosion management model can be deduced. This is due to the boom of this industry in the market, both in terms of distribution and production, and to the lack of knowledge of this phenomenon within their processes, since micro-enterprises are still structuring their management and quality methodologies. An additional condition for including management models beyond those required by food production standards is economic, as resources are limited and the results obtained depend mainly on direct demand—both from maquilas to third parties and from their own products;

otherwise, the financial sustainability of the sector is not viable. However, adequate strategic planning should aim at efficiency in all areas, and the development of a management model such as the corrosion model contributes to reducing maintenance costs by shifting the focus from corrective to preventive actions, guaranteeing the useful life of fixed assets, preserving their structure and metallic composition, and ensuring thorough control of potential contaminants for the benefit of food safety.

For the application of the Corrosion Management Model in craft breweries, it is important to evaluate performance using quantitative indicators, with objectives, clear action plans, and monitoring criteria that, when analyzed, determine the success or identify possible points of improvement for the proposed goals. When new processes must be created or standardized due to the implementation of the model, change management is required, involving and encouraging human talent to internalize the transversal importance of the model and to align their activities with the cycle of planning, execution, auditing, and action to ensure the continuous improvement of the industry.

This corrosion management model, as presented in Figure 7, proposes a cyclic structure, from the identification of needs to the publication of the policy, which allows certain phases to be executed in parallel among different areas. The first phase, identification—focused on internal and external requirements and functional risks—aims to identify possible causes of corrosion problems, guiding the alignment phase toward collaboration among the technical areas that may be involved, highlighting elements related to maintenance, cleaning, safety, and equipment useful life.

The results of the performance indicators and monitoring criteria established in the performance evaluation phase provide the basis for strengthening continuous improvement, in which difficulties that have not yet been addressed in corrosion management—due to the dynamics of the phenomenon—are periodically analyzed, conducting internal diagnostics for improvement plans.

To conclude, once the positive impact of the management system has been demonstrated, an overall business policy is defined in order to achieve economic benefits by reducing maintenance costs, organizational benefits by improving quality, and productive benefits by ensuring the useful life of equipment and avoiding reprocessing. For the model to be effective, it is necessary to maintain transparent and secure document management that promotes knowledge transfer within craft breweries. Ultimately, corrosion management contributes to the growth of the industry and, in the case of craft breweries, to the quality of the finished product, which can be directly affected by this physicochemical reaction.

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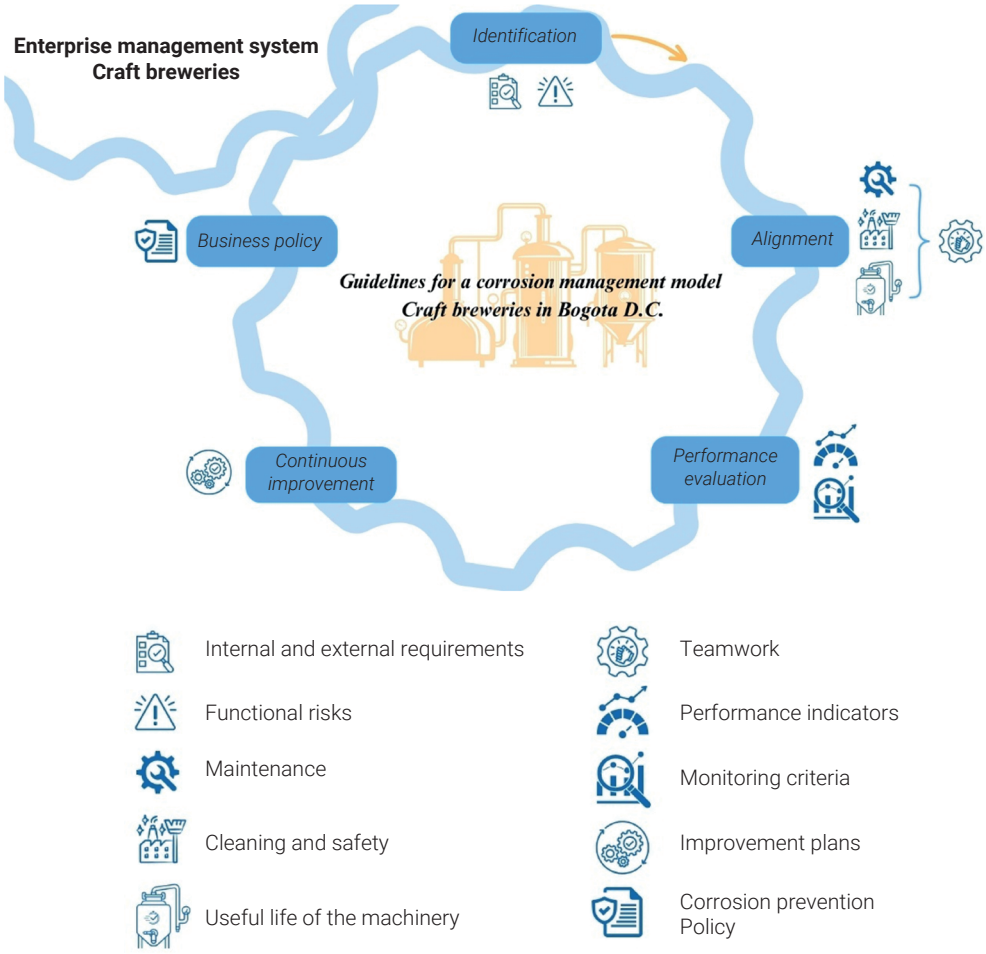

Figure 7. Proposed guidelines for a Corrosion Management Model for Craft Breweries.
Source: own work

CONCLUSIONS

For proper corrosion management in craft breweries, it is important to establish strategies to prevent and control the phenomenon, ensuring synergy and alignment with other management systems and determining solutions regarding the possible economic and productive impacts that affect process dynamics, market positioning, and human talent.

The application of the segmented survey in craft breweries made it possible to identify the general aspects of the sector and the specific dynamics of each company, along with their relationship to corrosion. Therefore, for the proposed guidelines of a

Corrosion Management Model, it was essential to identify the impact of the phenomenon on the economic factor, where specific corrosion expenses are not differentiated. This prevents an analysis of the direct damage to the company's estimated budget, which is also affected by the reduced useful life of equipment due to material wear, generating additional investments to replace deteriorated parts and requiring specialized suppliers. Regarding the productive factor, environmental conditions and maintenance are relevant aspects, as they contribute to reducing risks related to production and product quality. Likewise, the use of cleaning products that are not always compatible with the equipment can trigger unexpected reactions that damage the machinery and affect the beer's safety. As it is a food product, the minimum required safety and quality are governed by state regulations developed by INVIMA, which establish legal and technical requirements that contribute to process efficiency and transversality.

The main corrosion issues observed in the equipment used in the craft brewing industry are concentrated in joints, welds, moving or interchangeable parts, and contact points between different metals without protective layers, making it necessary to control inventories of low-complexity spare parts and perform periodic reviews of these focal points. Moreover, this phenomenon can occur in any metallic area, making it difficult to identify at the exact moment of its manifestation. For this reason, various studies have focused on the development of simulation systems and advanced computing, which are key in determining the causes of corrosion at an early stage.

Finally, the development of the proposed corrosion management model for the craft brewing industry in Bogotá D.C., applied to the activities of the production process, seeks to benefit SMEs, since by making an additional economic and time investment for corrosion control and management, personnel can be trained in preventive maintenance, adequate cleaning supplies, and good manufacturing practices. This reduces the probability of unexpected and immediate expenses, and generates a corrosion management policy based on the results of implementing the model's guidelines, which in the medium or long term will guarantee industry growth and continuous improvement.

For further studies on corrosion management, it is recommended to analyze the implementation of the proposed guidelines by making comparisons with models developed in the traditional brewing industry. Likewise, the guidelines should be replicated—with the necessary adjustments—for food and beverage industries that use machinery and equipment susceptible to corrosion in their production processes. Furthermore, considering the scope of the proposal, it is recommended to complement the results obtained for corrosion prevention with predictive models for controlling this phenomenon, as suggested in article [53].

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