Tecnura

Tecnologia y cultura, afirmando el conocimiento

Universidad Distrital Francisco Jose de Caldas
Facultad Tecnologica

Volumen 29 - Numero 86
Octubre - Diciembre de 2025

p-ISSN: 0123-921X
e-ISSN: 2248-7638

UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Revista TECNURA
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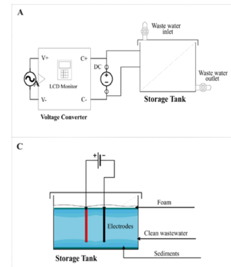

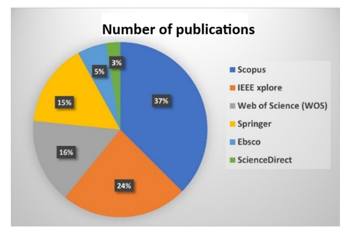

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INVESTIGACIÓN

NOTA DEL EDITOR

Editorial del Volumen 29 - Numero 86, 2025

Editorial

Tecnura llega al cierre de 2025 con el volumen 29, núm. 86, y es momento de dejar de tratar la ética en la investigación como un formulario que algunos consideran engorroso y que se llena al final para cumplir con un comité. En ingeniería, la ética suele quedar sepultada bajo la eficiencia, el costo y la presión por el desarrollo de un proyecto, en el que uno de los productos esperados es la publicación de resultados. No se trata de abordar el moralismo abstracto, sino de la responsabilidad concreta sobre los datos: ¿qué tan honestos somos cuando los algoritmos de IA empiezan a «alucinar» o a sesgar resultados? ¿Qué se sacrifica en la carrera por la optimización? Ahora más que nunca, la integridad científica se ha vuelto la moneda de valor real. Investigar con rigor no es solo aplicar bien la ecuación para llegar al resultado esperado —ya sea un hardware o un software—; es cuestionar el impacto de esa ecuación antes de que se vuelva infraestructura, es sostener la mirada frente a los resultados, incluso cuando no coinciden con la hipótesis inicial.

Este número busca sacar la ética de los pies de página para ponerla en el centro del desarrollo ingenieril, marcando la importancia de la responsabilidad de quienes generan conocimiento. Hay algo que atraviesa varios de los artículos de este número: la tensión entre velocidad y rigor. No es nueva, pero ahora pesa más. Publicar rápido, mostrar impacto, responder a métricas… y en medio de eso, sostener prácticas limpias.

En esta edición encontrarán artículos que involucran la integridad científica en el manejo de datos, la responsabilidad sociotécnica, la inteligencia artificial y el posible sesgo, entre otros aspectos concernientes a la ética en investigación. Se publican escritos que despliegan la ingeniería aplicada, que van desde el tratamiento de aguas residuales hasta la analítica de negocios, manteniendo como eje la búsqueda de eficiencia en sistemas que, por naturaleza, son complejos:

El tratamiento de efluentes domina una parte del volumen con un enfoque pragmático. Por un lado, se apuesta por la flotación por aire disperso con burbujas para el tratamiento de aguas cárnicas, buscando una solución mecánica funcional para la carga orgánica de esta industria. En paralelo, se aborda la electrocoagulación como una herramienta emergente y versátil, capaz de tratar las aguas residuales en diversos sectores empresariales.

El aprovechamiento de subproductos se ilustra a través de la transformación del suero lácteo en un producto funcional mediante la técnica de *spray drying*: un enfoque de ingeniería de procesos aplicada a la economía circular que convierte un contaminante potencial en un insumo con valor agregado.

El manejo de datos en las áreas de salud y agro se muestra, por una parte, en el uso de imágenes multiespectrales y regresión para estimar la biomasa en sistemas cacaoteros colombianos, con una perspectiva de agricultura de precisión que entiende que para gestionar el carbono hay que medirlo con rigor desde el aire. Por otra parte, en el ámbito clínico, se expone el análisis de clústeres para el reingreso de pacientes diabéticos, usando clasificadores para conformar grupos específicos según determinadas características y predecir situaciones de riesgo que podrían derivar en un nuevo ingreso a urgencias.

La gestión y estrategia para la sostenibilidad se abordan con el análisis bibliométrico sobre la gestión sostenible de la cadena de suministro (SSCM) en pymes, dejando claro que la presión ambiental ya no es exclusiva de las multinacionales; las pymes enfrentan sus propios retos con recursos limitados, y este estudio mapea caminos hacia su sostenibilidad. Adicionalmente, se presenta un mapeo sistémico sobre inteligencia de negocios (BI), que identifica que entre 2017 y 2024 la tendencia se desplazó marcadamente hacia el *machine learning* y el BI en tiempo real, aunque con una advertencia: la ética y la gobernanza de datos requieren atención urgente.

En resumen, este volumen es una muestra de ingeniería con poca retórica y más soluciones para el agua, el agro, la salud y la cadena de suministro, donde optimizar procesos, entender sistemas complejos y tomar decisiones con mejor información es una vía para lograr avance tecnológico con impacto ético.

La ingeniería sin conciencia es solo técnica aplicada. Aquí se prefiere la ciencia que se atreve a dudar.

Agradecemos a los autores por confiar sus trabajos a *Tecnura* y a los evaluadores por su lectura atenta, crítica y responsable. Su labor, muchas veces silenciosa, es la que sostiene la calidad y la credibilidad de cada número que llega a manos de la comunidad académica.

Cordialmente,

Ing. Lely A. Luengas-C., PhD
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Tecnura

https://revistas.udistrital.edu.co/index.php/Tecnura/issue/view/1277

DOI: https://doi.org/10.14483/22487638.22579

INVESTIGACIÓN

Aboveground Biomass Estimation of Colombian Cocoa Agroforestry Systems using Multispectral Images and Regression Methods

Estimación de la biomasa aérea de sistemas agroforestales cacaoteros colombianos mediante imágenes multiespectrales y métodos de regresión

Claudia V. Correa [1], Tatiana Gélvez-Barrera [2], Laura V Galvis G [3], Edwin Vargas [4], Jonathan Monsalve [5], Ariolfo Camacho [6], Iván Ramírez [7], Hoover Rueda-Chacón [8]

Fecha de Recepción: 14 de agosto de 2024 **Fecha de Aceptación:** 2 de diciembre de 2025

Cómo citar: Correa., C. V., Gélvez-Barrera., T., Galvis., L. V., Vargas., E., Monsalve., J., Camacho., A., Ramírez., I, and Rueda-Chacón., H. (2025). Aboveground Biomass Estimation of Colombian Cocoa Agroforestry Systems using Multispectral Images and Regression Methods. *Tecnura*, 29(86), 3–16. https://doi.org/10.14483/22487638.22579

Abstract

Context: Aboveground biomass (AGB) estimation for agricultural and environmental applications traditionally relies on time-consuming manual methods at ground level. Emerging approaches use remote sensing data evaluating spectral responses and vegetation indices in order to estimate the AGB more efficiently. Nonetheless, such techniques face various challenges in accounting for complex spatial distributions, especially when dealing with agroforestry systems (AFS).

Objective: This work aimed to estimate AGB in a Colombian cocoa AFS from multispectral images acquired with an un-manned aerial vehicle (UAV).

Methodology: In this work, the AGB was estimated by computing different vegetation indices from the measured spectral reflectances and evaluating two linear regression models, i.e., principal component regression (PCR) and partial least squares regression (PLSR), as well as a nonlinear regression model, a neural network composed by a perceptron with a single layer. Control points were obtained via on-ground biomass manual acquisition.

Results: Numerical experiments resulted in a coefficient of determination of R2 = 0.58 for the best linear model, while the non-linear model reached R2 = 0.86.

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Conclusions: AGB estimation in a cocoa AFS can be effectively performed using multispectral data acquired with a UAV and a simple nonlinear regression model.

Keywords: aboveground biomass estimation, agroforestry systems, cocoa, multispectral images, regression methods

Resumen

Contexto: La estimación de la biomasa aérea (AGB) para aplicaciones agrícolas y ambientales tradicionalmente se basa en métodos manuales a nivel del suelo que requieren mucho tiempo. Los enfoques emergentes utilizan datos de teledetección que evalúan respuestas espectrales e índices de vegetación para estimar la AGB de una manera más eficiente. No obstante, estas técnicas enfrentan varios desafíos a la hora de tener en cuenta distribuciones espaciales complejas, especialmente en sistemas agroforestales (SAF).

Objetivo: Este trabajo buscó estimar la AGB en un SAF de cacao colombiano a partir de imágenes multiespectrales adquiridas con un vehículo aéreo no tripulado (UAV).

Métodología: En este trabajo se estimó la AGB calculando diferentes índices de vegetación a partir de reflectancias espectrales medidas y evaluando dos modelos de regresión lineal, i.e., regresión de componentes principales (PCR) y

regresión de mínimos cuadrados parciales (PLSR), y un modelo de regresión no lineal, una red neuronal de un solo per-ceptrón. Los puntos de control se obtuvieron mediante una adquisición manual de biomasa en tierra.

Resultados: Los experimentos numéricos dieron como resultado un coeficiente de determinación de R2 = 0.58 para el mejor modelo lineal, mientras que el modelo no lineal alcanzó un R2 = 0.86.

Conclusiones: Es posible realizar una estimación eficaz de la AGB en un sistema agroforestal de cacao a partir de datos multiespectrales adquiridos con un UAV y un modelo de regresión no lineal simple.

Palabras clave: estimación biomasa aérea, sistemas agroforestales, cacao, imágenes multiespectrales, métodos de re-gresión

Introduction

Biomass is the largest and most important renewable source that is currently available and can be used to produce different forms of energy. It is currently the fourth largest energy source after coal, oil, and natural gas [1]. Given that forests have an inherent ability to retain carbon dioxide and can regulate the cycling of carbon, interest in estimating forest biomass has increased.

The aboveground biomass (AGB) measures the amount of organic matter in living and dead plant materials [2, 3], which is a critical indicator of plant health. It is expressed as oven-dry tons per unit, including leaves, twigs, branches, the main bole, and the bark [4]. Therefore, it is widely used in smart and precision agriculture for growth crop monitoring [5] and environmental applications such as carbon sequestration monitoring [6].

Traditional AGB estimation methods are based on manual sampling and dry weight calculations, which destroy the samples [7, 8]. Alternative methods employ tree level measures to generate allometric functions aimed at evaluating the ground-level biomass, and extrapolation methods are later used to assess the whole area [7, 9–12]. These methods, however, are time-consuming and expensive considering the extensive areas that must be covered [6].

Recently, remotely sensed data from satellites and unmanned aerial vehicles (UAVs) have been used as a more practical method for biomass mapping and estimation in larger study areas [13–15]. Remote sensing data contain information on the spectral response, density, shade, and texture of the vegetation cover, which is related to various indices [16] and can therefore be used to estimate the AGB [8]. To name a few, the authors of [7] use spaceborne optical, synthetic aperture radar (SAR), and light detection and ranging (LiDAR) data to estimate AGB in agroforestry systems (AFS) while focusing on varying climate conditions. In [18], UAV LiDAR data and multispectral satellite images are used along with topographic correction methods for AGB estimation, providing a new indicator in mountain grassland applications. In [19], the AGB in sorghum is estimated via machine learning techniques, exploiting the relationship between vegetation indices and sorghum AGB for different spatial resolutions. Further methods have estimated biomass using multispectral UAV imagery from crops such as dry strawberry [20] and potato [21].

AGB estimation through remotely sensed data has become relevant in AFS, where vegetation, crop density, and sometimes livestock are combined. Specifically, AFS are a diverse and sustainable farming approach that combines agriculture and forestry, optimizing land use and contributing to environmental conservation, sustainable development and ensuring long-term productivity [22]. In Colombia, cocoa AFS have become popular due to their potential for supporting sustainable development and providing alternative livelihoods in areas previously affected by conflict [23, 24]. In addition, cocoa is one of the most representative products for the Colombian economy, not only for internal consumption but also for international trading [25, 26]. Previous works on cocoa AFS in Colombia have investigated the carbon storage potential and productivity in the southwest of the country [23, 27] by employing different allometric models.

The accurate estimation of AGB from remote sensing data still faces limitations, including the difficulty of considering the variability in the spatial distribution, structure, and composition of AFS

[28]. Furthermore, particularly for Colombia, there is still a strong dependence on traditional on-site crop measurements as well as on destructive AGB methods. In light of the above, this work aims to explore the potential of remotely acquired spectral imagery and machine learning to estimate the AGB in a Colombian cocoa AFS.

Specifically, this work employed a UAV to collect multispectral images over an AFS located in a northeastern region of Colombia, in addition to a set of on-site biomass control points manually calculated through allometric equations. The proposed pipeline to analyze and calculate the AGB included

(i) the calculation of vegetation indices (VIs) from the spectral bands, (ii) a correlation analysis between the predictors (spectral bands and VIs) and the observed biomass, and (iii) the performance analysis of two multivariate linear regression models, *i.e.*, principal component regression (PCR) [29, 30] and partial least squares regression (PLSR) [31], and a nonlinear regression model, a neural network (NN) [32]. The results demonstrate that the near-infrared (NIR) and green spectral bands, along with the normalized difference vegetation index (NDVI), provide the highest correlation with the AGB of the cocoa AFS. The best model achieves a coefficient of determination as high as $R^2 = 0.86$.

Methodology

This section describes the study area and summarizes the methods used to estimate the AGB from multispectral imagery.

Study area

The study area is an 896×726 m^2 region in the northeastern part of Colombia, as highlighted in Figure 1a. Particularly, this area is located at 6°51'N, 73°24'W, in the municipality of San Vicente de Chucurí, Department of Santander. In Figure **1**b, the red line traces the entire municipality, and the small blue box limits the observed region: a mountainous agricultural area with a cocoa AFS. As shown in Figures 1c-d, the yellow box highlights the cocoa trees, which were manually located and segmented.

At-ground allometric biomass measurements

40 cocoa trees (*Theobroma cacao*) were manually measured at ground level, including height and diameter, and later analyzed. Following the work of [33], we used an allometric equation to calculate the cacao species biomass in individual trees:

$$\text{Biomass} = 10^{-1{,}625 + 2{,}63 \times \log 10(d30)} \tag{1}$$

where d_{30} refers to the tree trunk diameter at a height of 30 cm. Based on Equation (1), the observed biomass for the 40 cocoa trees ranges from 3 to 25 kilograms per tree.

Aboveground multispectral measurements

Multispectral images were acquired using a Parrot Sequoia multispectral camera mounted on a UAV at a height of 100 m, at 10:15 am, with image overlap of 75%. This camera has a synchronized array of four single-band cameras, each with a 1.2 MP sensor featuring a 3.75 µm pixel pitch and a 4 mm lens, but with a different interference filter in front. The interference filters employed by this camera span along the green (G: 530 to 570 nm), red (R: 640 to 680 nm), red-edge (RE: 730 to 740 nm), and near-infrared (NIR: 770 to 810 nm) spectral bands. The acquired images have a resolution of 7474 × 6053 pixels, with a ground sample distance (GSD) of 12 cm. Agisoft Metashape and its automatic reflectance calibration procedures were used to generate the orthomosaic.

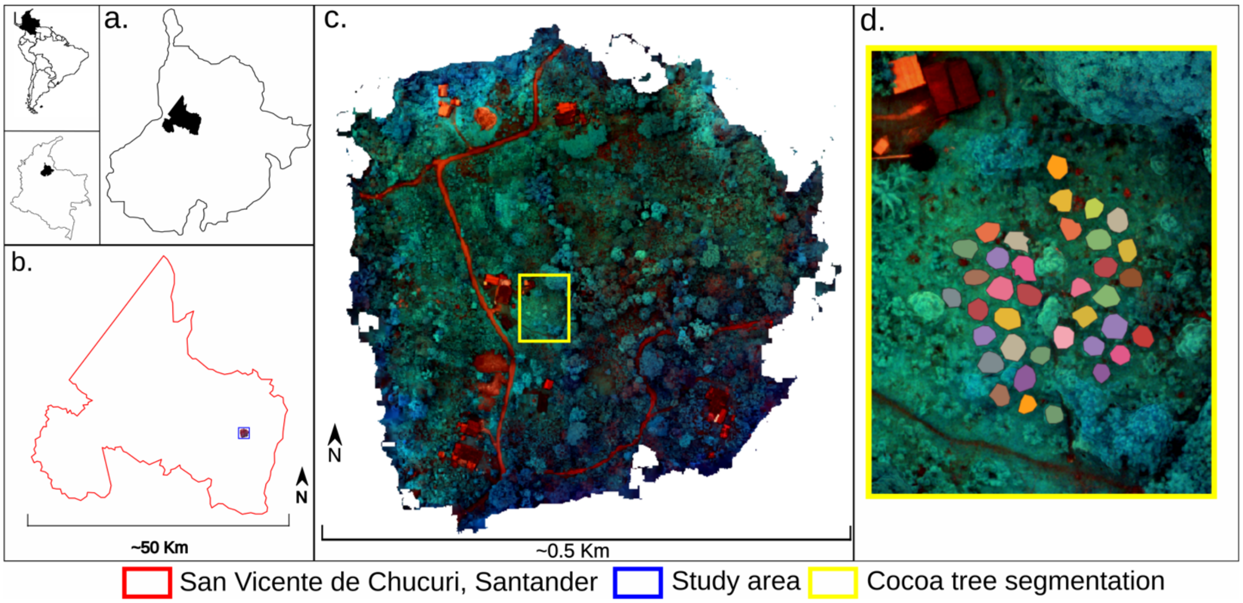


Figure 1. a) Study area located at 6°51'N, 73°24'W in San Vicente de Chucuri, Santander, Colombia. b) The red line traces the entire municipality, while the small blue box limits the observed region. c) Mountainous area with the AFS under analysis. d)Yellow box showing the cocoa tree segmentation.

Calculating VIs

VIs are calculated based on the ratio between two or more bands to contrast the high absorption by leaf pigments (chlorophylls, carotenoids, and xanthophylls) in the visible spectral region (400–700 nm) and the high reflectance by leaves in the NIR region (700–1300 nm). For this study, we chose six of the most representative VIs that have been associated with AGB in the state of the art [16]: the NDVI, GNDVI, NDRE, RDVI, CVI, and OSAVI. Table 1 shows the formulas used to calculate each index.

Regression models for AGB estimation

We considered two regression approaches to estimate AGB from multispectral information and calculated VIs. The first uses linear regressions such as PCR and PLSR. The second uses a learning-based perceptron that captures nonlinear relationships between the predictors.

PCR and PLS regression

For the linear regression method, let $\mathbf{y} \in \mathrm{R}^m$ denote a column vector with the m observed bio-mass values, and $\mathbf{X} \in \mathrm{R}^{m \times n}$ a matrix with the n predictors (four spectral bands and six VIs), for each m-th observation. Thus, a linear model of the form $\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \epsilon$ can be established, where $\boldsymbol{\beta} \in \mathrm{R}^n$ is the vector of coefficients to be estimated and $\epsilon \in \mathrm{R}^m$ accounts for the approximation error. These coefficients are commonly estimated via ordinary least squares. However, due to the high correlations within the spectral variables, PCR and PLSR are preferred; they break such correlations by projecting the original data onto a lower-dimensional subspace.

Mathematically, the projection of the matrix **X** to a new subspace can be represented as $\mathbf{C} = \mathbf{X}\mathbf{W}^T$, where $\mathbf{W} \in \mathrm{R}^{r\times n}$ is known as the projection matrix and $\mathbf{C} \in \mathrm{R}^{m\times r}$ contains r linearly independent variables, *i.e.*, the principal components or scores. When **W** is calculated using the SIMPLS algorithm [34], **C** contains the PLS coefficients. Furthermore, when **C** is employed instead of **X**, the regression model becomes, $\mathbf{y}' = \mathbf{X}\boldsymbol{\beta}' + \epsilon'$, with $\boldsymbol{\beta}' = \boldsymbol{\beta}\mathbf{Q}^T$, where $\mathbf{Q} \in \mathrm{R}^{n\times r}$ represents the PLS regression over the observation vector **y**. PLS uses the observed samples **y** to construct **W** and **Q**, to obtain linearly independent variables from **X**, which are maximally correlated with the known observations.

Nonlinear regression model

To consider nonlinear interactions between the n predictors, we explored the use of NNs, introducing nonlinearity through activation functions [35]. In mathematical terms, let $\{\mathbf{x}_i, \mathbf{y}_i\}$ be the paired training dataset for $i = 1, \ldots, m$, where $\mathbf{y}_i$ denotes the i-th observed biomass and $\mathbf{x}_i \in \mathrm{R}^n$ contains the corresponding predictors (rows of **X**). A neural network G_θ, with trainable weights can learn the coefficients to predict the AGB from the multispectral predictors, obtaining the optimal weights by solving the following optimization problem:

$$\theta^* \varepsilon \arg\min_\theta \left\{ \frac{1}{m} \sum_{i=1}^{m} L(x_i, G_\theta(y_i)) \right\} \quad (2)$$

where $L(\cdot)$ denotes the loss function. The model architecture includes an input layer that receives the predictors as the input, a flatten layer, and a dense layer that outputs predictions with the specified number of classes. We selected the mean-squared error (MSE) as the loss function and used the adaptive moment estimation (ADAM) optimizer, with the activation function set to be the parametric rectified linear unit (PReLU) [32].

Results

This section reports on the results obtained to estimate the AGB from remote sensing data via the linear and nonlinear regression models. Firstly, a correlation analysis is conducted to study how the predictors are correlated between them and to the observed biomass measured at ground level. Then, we present the results obtained with the two regression methodologies. We used the coefficient of determination (R^2) and the root-mean-squared error (RMSE) to evaluate their performance. In this section, note that B1 refers to the green (B) band, B2 to the red (R) band, B3 to the red-edge (RE) band, and B4 to the near-infrared (NIR) band of the multispectral images.

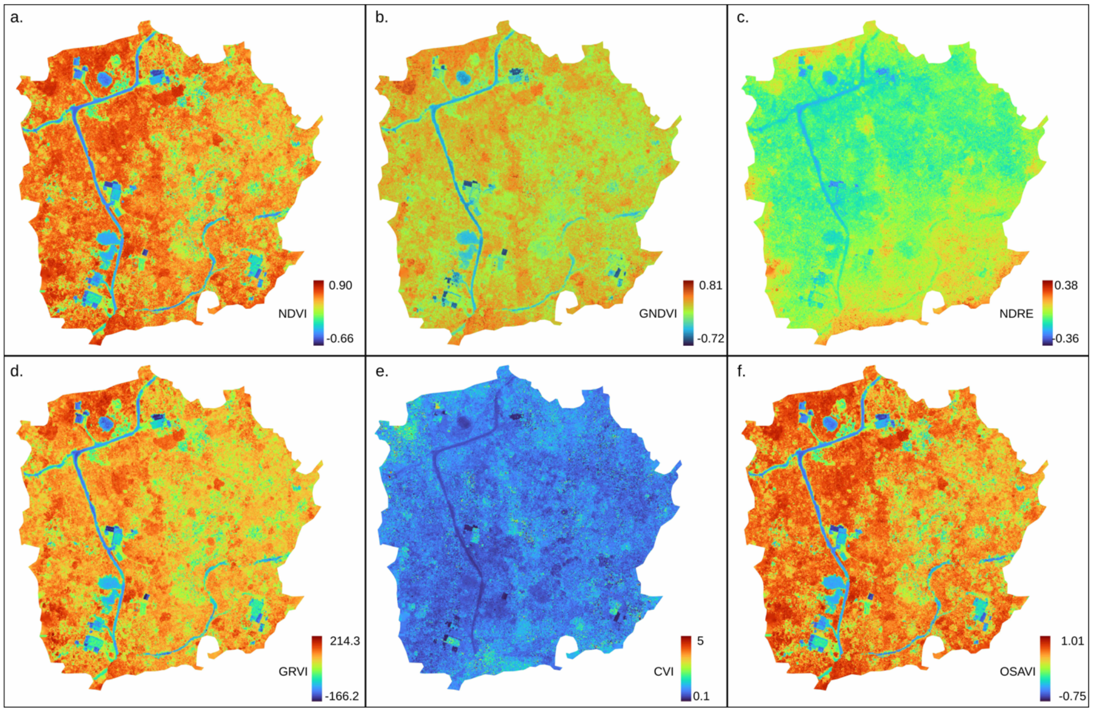


Figure 2. Maps of the cocoa AFS for the six vegetation indices under analysis: a) NDVI, b) GNDVI, c) NDRE, d) GRVI, e) CVI, and f) OSAVI.

VI maps

40 biomass data points were measured at ground level using the allometric Equation (1), and they were assumed to be the ground truth control points. The multispectral dataset was acquired in the same region where the cocoa trees were present, as detailed in Figure 1, and the 40 cocoa trees were manually segmented to calculate the averaged reflectance, with which we calculated the VIs. For reference, the maps of the calculated vegetation indices for the full cocoa AFS are shown in Figure 2.

Correlation analysis

The predictors were correlated between them and against the biomass. Figure 3 shows that the greatest correlation with biomass comes from the red-edge band (B3=0.24), followed by green (B1=0.19) and red (B2=0.19). As expected, higher correlation values were obtained between the spectral bands and the VIs. For instance, B1 and GNDVI have a correlation of -0.94, B2 and NDVI exhibit -0.96, and B2 and RDVI report -0.90.

Furthermore, an exploratory analysis was performed to determine the data variance explained by the principal components. Given the bias-variance trade-off, selecting many components may lead to overfitting, and too few may cause underfitting. Thus, keeping the minimum number of components before explained data variance plateaus yields minimal information loss and greater prediction power.

Figure 4a shows that two components explain more than 95% of the variance in **X**, while at least six components are required to explain 40% of the biomass (**y**). Figure 4b shows the score plot where the dominant predictors for the first two principal components (PC1 and PC2) explain 95% of the variance. In particular, CVI and GNDVI are in the PC1-positive and PC2-positive quadrant; NDRE, B4, RDVI, NDVI, and OSAVI are in the PC1-positive and PC2-negative quadrant; B2 is in the PC1-negative and PC2-positive quadrant; and B1 is in the PC1-negative and PC2-negative quadrant.

AGB estimation using PCR and PLSR

The PCR and PLSR algorithms were run following a cross-validation strategy with 70-30% partitions. The spectral variables were mean-centered and normalized. Furthermore, singular value decomposition (SVD) and the SIMPLS algorithm were used to estimate the PCA and PLS components, respectively. We evaluated the R^2 and the RMSE to address the variable selection step. Fig. 5a summarizes the statistics of different models, varying the number of components from 1 to 10. The results suggest that the best prediction model (high R^2 and low RMSE) is attained with seven components, with an averaged $R^2 = 0.58$ (Fig. 5b), and an RMSE of prediction of 3.44 for both PCR and PLSR, as shown in Fig. 5c. The latter suggests and error of around (3.4499/25) * 100% = 13.80% in the maximum biomass value reported (25 kg/tree).

AGB estimation using nonlinear regression

To evaluate the performance of the regression NN, and given the limited number of samples ($m = 40$), we employed a k-fold cross-validation strategy to avoid optimistic bias and obtain a more reliable estimate of generalization performance. We carried out a k-fold cross-validation for $k = [2, 4, 6, 8]$, *i.e.*, we used k samples for validation and $m - k$ samples for training. The learning rate was fixed to $8e^{-3}$ using 600 epochs. The dataset was normalized with respect to the maximum. For each experiment, Fig. 6a reports the mean and standard deviation, where we obtained up to $R^2 = 0.8589$ for the prediction task (Fig. 6b) and a prediction RMSE of 2.090 (Fig. 6c). The latter suggests and error of around (2.090/25) * 100% = 8.36% in the maximum biomass value reported (25 kg/tree). The high variance in the models is due to the few available training points. Such behavior can be improved when more data become available.

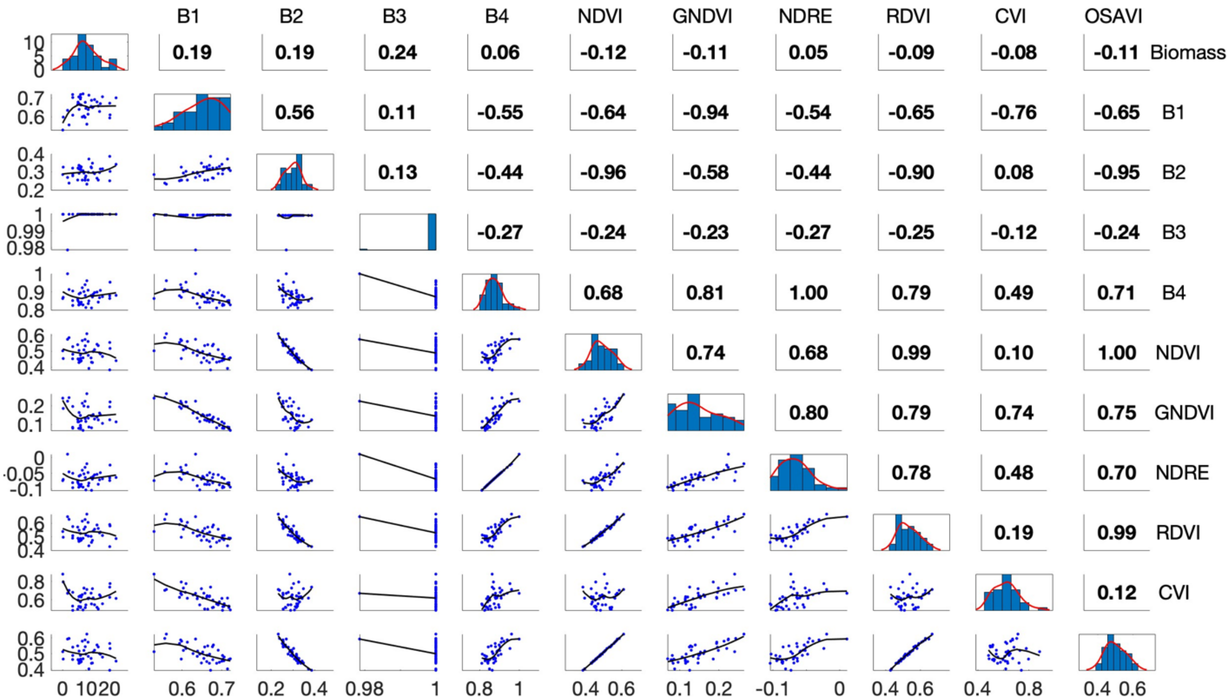
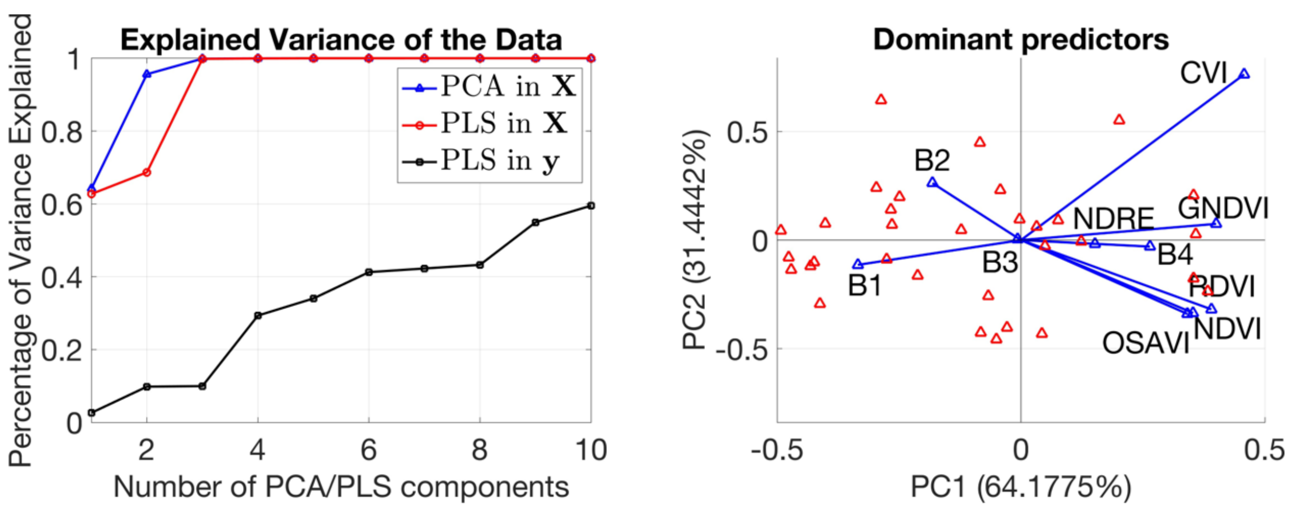
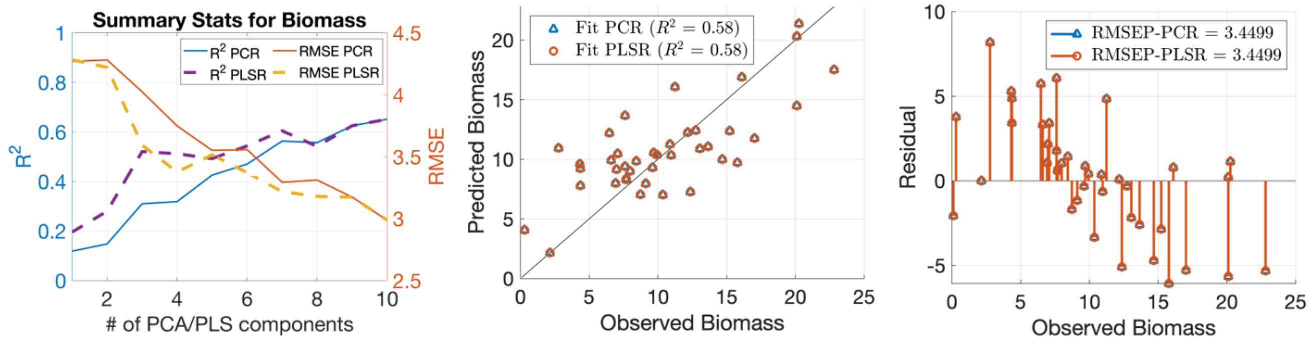


Figure 3. Correlation plot between biomass and predictors. Greater correlation comes from B3 (0.24), B1, and B2 (0.19). Higher correlation values are observed between spectral bands and vegetation indices, as expected.



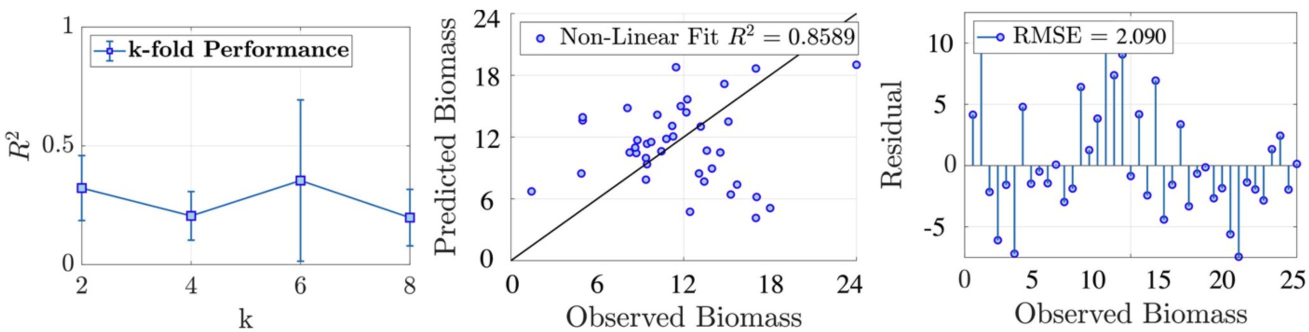
(a) (b)

Figure 4. a) Explained variance *vs.* number of components (two components explain over 95% of the variance in **X**, while at least six are required to explain 40% of the biomass). b) Score plot showing the dominant predictors for the first two principal components (PC1 on the *x*-axis and PC2 on the *y*-axis).



(a) (b) (c)

Figure 5. PCR/PLSR results. a) Summary of different regression models with varying number of components. b) The best fitting result with seven components. c) Residuals of best fit.



(a) (b) (c)

Figure 6. a) Average performance of nonlinear regression for different k-folds. b) Best fitting result. c) Best fit residuals.

Discussion

Overall, the results demonstrate the potential of multispectral UAV imagery combined with regression techniques to estimate AGB in Colombian cocoa AFS. The correlation analysis showed that, although individual predictors such as the red-edge band have moderate correlations with biomass (B3=0.24), the predictors are highly intercorrelated. This supports the selection of few predictors that ensure a good model fit while preventing overfitting, with seven components providing the best trade-off. The best linear models reached $R^2 = 0.58$, suggesting that they cannot fully represent complex spectral–biomass relationships. In contrast, the nonlinear NN improved performance, achieving $R^2 = 0.86$ and reducing the RMSE to 2.090 kg/tree (8.36% of the maximum biomass), highlighting the importance of nonlinear interactions in heterogeneous AFS. These results indicate that comparable AGB estimation performance can be achieved with smaller, lower-resolution datasets, in contrast to recent studies on strawberry [20] and potato [21] crops in different countries, which used large, very high-resolution (2 cm) multitemporal datasets and reported R^2 values around 0.8.

From a practical perspective, this methodology could be used by institutions such as FEDECA-CAO as a scalable tool for monitoring cocoa AFS. Specifically, periodic UAV-based multispectral surveys combined with nonlinear models would generate spatially explicit AGB maps at farm or regional scales, thereby supporting carbon accounting and certification processes, as described in [36]. Additionally, these biomass maps could serve as indicators of crop health, facilitating the early identification of low-productivity areas and enabling targeted agronomic interventions.

Among the identified limitations, the small sample size (40 trees) likely contributed to variability in model performance and may restrict generalization to other cocoa farms. Second, the entirety of the UAV imagery was acquired on a single date. Therefore, models may be sensitive to phenological stage and seasonal variations. Finally, the atmospheric conditions present at the time of acquisition, such as cloud cover or illumination differences, could have influenced spectral reflectance, potentially affecting predictions.

Conclusions

This work estimated the AGB of a cocoa AFS in Colombia while employing a dataset of multispectral images acquired with an UAV, using linear regression models (PCR and PLSR) and a learning-based nonlinear regression model (NN). These models exploit at-ground biomass control points. Numerical experiments resulted in an $R^2 = 0.58$ for the best linear model, with an RMSE of 3.4499, whereas the non-linear model attained an $R^2 = 0.86$ and an RMSE of 2.090. In terms of percentage error, the best linear model yielded 13.80%, and the non-linear model reported only 8.36%. This suggests that a simple nonlinear regression model can better predict the biomass content of a cocoa AFS.

Future work should expand the analysis to include multiple acquisition dates across phenological stages and environmental conditions for temporal assessment. Additionally, integrating complementary data such as LiDAR-derived structural metrics or textural information from high-resolution imagery could enhance AGB estimation accuracy. Exploring advanced nonlinear modeling and ensemble methods may further improve prediction while maintaining operational scalability, strengthening UAV based biomass estimation in cocoa AFS.

Acknowledgments

The data used in this work were provided by the National Federation of Cacao Growers of Colombia (FEDECACAO).

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DOI: https://doi.org/10.14483/22487638.23696

INVESTIGACIÓN

Aprovechamiento de suero lácteo para el desarrollo de un producto funcional mediante tecnología de *spray drying*

Use of whey for the development of a functional product using spray drying technology

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Fecha de Recepción: 6 de junio de 2025 **Fecha de Aceptación:** 30 de noviembre de 2025

Cómo citar: A. R. Micanquer-Carlosama and J. F. Muñoz-Paredes (2025). Aprovechamiento de suero lácteo para el desarrollo de un producto funcional mediante tecnología de spray drying. *Tecnura*, 29(86), 17–35. https://doi.org/10.14483/22487638.23696

Abstract

Objective: To develop a powdered product based on sweet whey, blackberry pulp (Rubus glaucus), maltodextrin and inulin, using spray drying technology.

Methodology: the raw material was characterized physicochemically. The formulation of a suspension was optimized using a Box-Behnken type response surface experimental design. The independent variables were: blackberry pulp (0,30 – 0,50), sweet whey (0,30 – 0,50), maltodextrin (0,10 – 0,20), all in units of mass fraction; inulin was a fixed variable at 6 %. The dependent variables were; pH, soluble solids (°Brix) and viscosity (cP). The optimum suspension was dried by spray drying, the inlet air temperature factor was evaluated (130°C, 140°C and 150°C) with a unifactorial design and the dependent variables were: humidity (%), water activity (a_w), solubility (%), wettability (g/min), antioxidant capacity (ug/g) and color (L*a*b*). Sensory analysis (taste, odor, color and general acceptance) was performed with the best treatment.

Results: the optimal formulation of the suspension was blackberry pulp (0,419); whey (0,319); maltodextrin (0,202) and (0,060) inulin. The viscosity was 1.631 cP, pH 3,64 and 31,40 °Brix. The best treatment in the drying process was obtained at 130 °C, with a_w = 0,247±0.037, solubility = 60,44 ±0.53 %, wettability = 0,082±0.006 (g/min) and antioxidant capacity of 8,39±0.07 mg gallic acid/g. In the sensory analysis, a general acceptance of 4,4±0.6 on a scale of 1 to 5 was obtained.

Conclusions: the optimal formulation of the suspension allowed obtaining a powdered product with potential functional benefits for the consumer.

***Keywords*:** Functional, Spray drying, Whey, Suspension

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Resumen

Objetivo: desarrollar un producto en polvo a base de suero lácteo dulce, pulpa de mora (Rubus glaucus), maltodextrina e inulina, mediante tecnología spray drying.

Métodología: se caracterizó fisicoquímicamente la materia prima. Se optimizó la formulación de una suspensión, mediante un diseño experimental de superficie respuesta tipo Box-Behnken. Las variables independientes fueron; pulpa de mora (0,30 – 0,50), suero lácteo dulce (0,30 – 0,50), maltodextrina (0,10 – 0,20), todas en unidades de fracción másica, la inulina fue una variable fija al 6 %. Las variables dependientes fueron; pH, sólidos solubles (°Brix) y viscosidad (cP). La suspensión óptima se secó mediante *spray drying* y se evaluó el factor temperatura del aire de entrada (130 °C, 140 °C y 150 °C) con un diseño unifactorial y las variables dependientes fueron: Humedad (%), actividad de agua (a_w), solubilidad (%), humectabilidad (g/min), capacidad antioxidante (ug/g) y color (L*a*b*). Con el mejor tratamiento se realizó análisis sensorial (sabor, olor, color y aceptación general).

Resultados: la formulación óptima de la suspensión resultó con pulpa de mora (0,419); suero lácteo (0,319); maltodextrina (0,202) y (0,060) inulina. La viscosidad fue de 1.631 cP, pH 3,64 y 31,40 °Brix. El mejor tratamiento en el proceso de secado se obtuvo a 130 °C, con a_w = 0,247±0,037, solubilidad = 60,44 ±0,53 %, humectabilidad = 0.082±0.006 (g/min) y capacidad antioxidante de 8,39±0,07 mg ácido gálico/g. En el análisis sensorial se obtuvo una aceptación general de 4,4±0,6 en escala de 1 a 5.

Conclusiones: la formulación óptima de la suspensión permitió obtener un producto en polvo con potencial aporte funcional para el consumidor.

***Palabras clave*:** Funcional, Spray drying, Suero lácteo, Suspensión.

Introducción

En la industria del procesamiento de productos lácteos, el suero de la leche es un residuo de la elaboración de queso que incluye proteína, lactosa y otros elementos solubles en agua. Se estima que la producción anual de suero a nivel mundial oscila entre 180 a 190 millones de toneladas, con un incremento del 1 % al 2 %, de tal forma que para el año 2030, se espera una generación de alrededor de 203 a 241 millones de toneladas [1]. En décadas recientes, uno de sus usos ha sido la reincorporación en la misma línea de producción; sin embargo, la gran cantidad de suero producido ha generado problemas ambientales, debido a su alto contenido orgánico y a su alta demanda bioquímica de oxígeno [2]. De acuerdo con lo anterior, su uso para la elaboración de un alimento funcional aporta valor a la cadena productiva, ya que en la actualidad el suero es considerado como una fuente de ingredientes valiosos con beneficios multifuncionales [3], además de contribuir con la mitigación de los efectos ambientales.

La Mora de Castilla es un cultivo herbáceo anual, originario de las regiones tropicales montañosas de América, incluyendo países como Colombia, Ecuador, México, Panamá, Guatemala, Honduras y El Salvador. Esta fruta, forma parte de la familia *Rosaceae*, y es apetecida por su sabor, adaptabilidad y características nutritivas [4]. Investigaciones han evidenciado que la mora es rica en antioxidantes, como antocianinas y flavonoides, los cuales pueden tener efectos protectores sobre la salud cardiovascular y contribuir con la prevención de enfermedades crónicas [5].

Por otra parte, los alimentos funcionales son aquellos que ofrecen beneficios adicionales para la salud, incluso más allá del valor nutricional básico, ya que contienen compuestos bioactivos que mejoran la salud y reducen el riesgo de desarrollar enfermedades crónicas [6]. Hoy en día, esta nueva oferta de alimentos evoluciona muy rápido debido a las preferencias de los consumidores y a los cambios constantes en la normatividad de los países. Las tendencias actuales, muestran la relevancia en el aumento de la preferencia en el consumo de cereales integrales, frutas, verduras, además de productos con mayor contenido de proteína, igualmente, existe un creciente interés en productos con menor contenido de sal, grasa y azúcar [7].

En cuanto a la clasificación de estos alimentos funcionales, se pueden mencionar dos grandes grupos: los alimentos funcionales que se producen de forma natural, incluidos los alimentos mínimamente procesados que cuentan en sí mismos con propiedades beneficiosas para la salud; y, por otra parte, los alimentos funcionales modificados, es decir, aquellos en los cuales se ha introducido una alteración en su composición, con el fin de aumentar el contenido de componentes bioactivos o nutrientes específicos [8].

De acuerdo con lo anterior, el desarrollo de un prebiótico se encuentra dentro de la clasificación de alimentos funcionales modificados, con aportes fundamentales para mejorar la salud gastrointestinal de las personas [9]. Igualmente, la reutilización de lactosuero contribuye con la economía circular, con la conservación del ambiente, y contribuye a enfrentar los retos de seguridad alimentaria en las regiones de mayor producción de leche [10]. Tanto el suero lácteo como la pulpa de mora proporcionan elementos de gran valor nutricional. Por ejemplo, el suero de leche se compone del 5 % de lactosa, el 93 % de agua, el 0,85 % de proteína, el 0,53 % de minerales y el 0,36 % de grasa [11]. Por otro lado, la pulpa de mora proporciona nutrientes, antioxidantes, y posee características antiinflamatorias y quimiopreventivas, gracias a su composición rica en polifenoles [12].

Finalmente, el aprovechamiento de suero lácteo y pulpa de mora representa una alternativa viable para la elaboración de un producto funcional con propiedades prebióticas que contribuye a la valorización de subproductos agroindustriales, a la conservación de los recursos naturales, a la innovación tecnológica y a la investigación. Por todo lo anterior, esta investigación planteó, en primer lugar, la caracterización del suero lácteo y de la pulpa de mora con el fin de conocer las propiedades fisicoquímicas y el aporte en actividad antioxidante de estas materias primas; luego, la obtención de un producto en polvo mediante *spray drying*, una de las tecnologías viables económicamente para este tipo de productos y finalmente la caracterización química y sensorial del producto final.

Metodología

Materiales

Para la medición de las propiedades fisicoquímicas se utilizó *Buffer* estándar con pH 4 y 7 para la calibración del pH-metro, hidróxido de sodio (NaOH) al 0,1N para la titulación de acidez, fenolftaleína como indicador de pH, ácido sulfúrico (H_2SO_4) concentrado para la digestión en la determinación de proteínas, ácido bórico al 4 % para la valoración del nitrógeno total, etanol al 96 %, DPPH (2,2-difenil-1-picrilhidrazil) para antioxidantes y agua destilada.

Caracterización fisicoquímica del suero lácteo dulce y la pulpa de mora

La mora se obtuvo del mercado "potrerillo" en la ciudad de Pasto – Nariño (Colombia) y el suero lácteo dulce de una planta de procesamiento de lácteos ubicada en la misma ciudad. Las propiedades fisicoquímicas que se midieron en el suero fueron pH, acidez (%), sólidos totales (%), sólidos solubles (°Brix), proteínas (); y en la pulpa de mora (*Rubus glaucus*) se midieron pH, acidez (%), humedad (%), sólidos solubles (°Brix), capacidad antioxidante (ug/ml) y contenido de polifenoles (ug ácido gálico/g). El pH se midió según Norma Técnica Colombiana (NTC 3651:2012) [13], acidez se midió según NTC 4978. Sólidos solubles totales según NTC 4624. Sólidos totales según NTC-5283. Contenido de proteína y N_2 se llevó a cabo mediante digestión por el método Kjeldahl NTC 5025. Humedad se determinó según la AOAC (925.09) [13], Antioxidantes por método DPPH y polifenoles se determinaron según la metodología establecida en AOAC (925.09) [13]. Todas las mediciones se realizaron por triplicado.

Diseño experimental en la formulación de la suspensión y en el proceso de secado

Mediante un diseño de optimización de superficie de respuesta – Box-Behnken (ajuste de modelo de segundo orden) se optimizó la elaboración de la suspensión prebiótica. El diseño experimental se trabajó con valores de fracción másica con el condicional que el total de los componentes sumarán 1. Uno de los componentes (inulina) de la suspensión se trabajó como variable fija, con una participación fija del 0,060 (valor tomado con base a estudios previos). Los factores evaluados fueron: Factor 1, fracción de pulpa de mora (0,30 – 0,50). Factor 2, fracción de suero lácteo (0,30 – 0,50). Factor 3, fracción de maltodextrina (0,10 – 0,20), obteniendo un total de 15 tratamientos. Las variables dependientes evaluadas fueron pH, sólidos solubles (°Brix) y viscosidad (cP). Todas las mediciones se midieron por triplicado.

En el proceso de secado (figura 1) se evaluó el efecto de la temperatura del aire de entrada en el equipo de secado *spray drying* con tres niveles 130 °C, 140 °C y 150 °C, sobre las propiedades fisicoquímicas del producto en polvo mediante un diseño unifactorial con un total de seis tratamientos. El proceso de secado se llevó a cabo en condiciones controladas, garantizando la reproducibilidad de los tratamientos. Se determinaron las variables, capacidad antioxidante (ug/g), actividad de agua (a_w), solubilidad (%), humectabilidad (g/min) y color en unidades CieL*a*b*. Todas las mediciones se realizaron por triplicado.

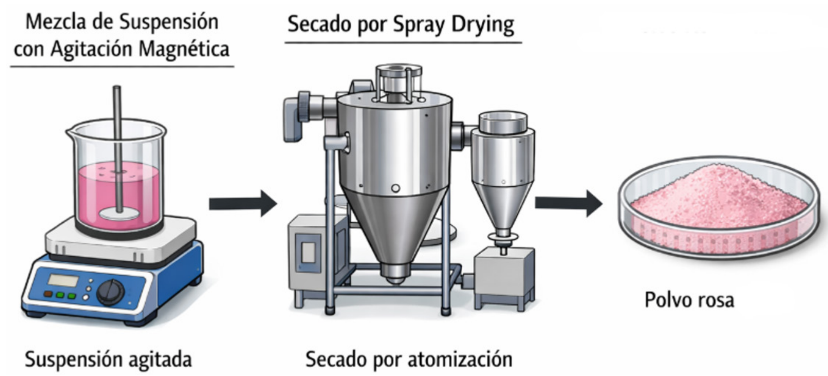

Figura 1: Representación del proceso de secado por spray drying en la obtención de un producto en polvo.

Nota: elaboración propia.

Caracterización fisicoquímica de la suspensión

El pH se midió mediante metodología establecida en [13]. Los sólidos solubles totales según NTC 4624. La viscosidad se midió con un viscosímetro de husillo N°3 a 30 rpm, como se describe en la metodología descrita por [14]. Los resultados se reportaron en cP.

Caracterización fisicoquímica del polvo obtenido del proceso de secado

Se determinó la actividad antioxidante mediante método DPPH [15], actividad de agua se midió en un higrómetro de punto de rocío a 20°C (AquaLab 3TE, USA), Solubilidad y humectabilidad se determinaron según la metodología de [16], con modificaciones. Para la solubilidad se trabajó con una dilución de 10 mL de agua destilada/0,1 g de polvo. Se centrifugó a 3100 rpm por 10 min. Se tomó una alícuota de 2,5 mL del sobrenadante y se secó en estufa convectiva a 105 °C por 1 h.

Para la humectabilidad se pesó 1 g de polvo y se adicionó en 500 ml de agua, el tiempo que tarda en sumergirse totalmente el polvo se registró en unidades de g/min. Y color se midió utilizando un colorímetro (LUTRON RGB-1002). Los resultados se reportaron en coordenadas CIELAB (*L**, *a**, *b**). Donde el valor "*L**" se utiliza para denotar luminosidad (+) y oscuridad (-); valores de "*a**" rojo (+) y verde (-); valores de "*b**" amarillo (+) y azulado (-) [17].

Análisis sensorial

Se realizó un análisis sensorial para la determinación del grado de aceptación del producto en polvo obtenido (mejor tratamiento en el proceso de secado), en la cual se evaluaron los atributos: color, sabor, olor, textura y aceptación general con un panel de 30 catadores no entrenados [15]. Estos se seleccionaron de una población de personas mayores de 18 años (género masculino y femenino) de un municipio del departamento de Nariño (Colombia). La muestra de la población se seleccionó con base en un segmento de población de uno de los municipios de alta producción de derivados lácteos en los cuales la necesidad del aprovechamiento del suero lácteo es evidente. Las muestras para cada panelista fueron de 1 g, entregado en recipiente plástico color blanco desechables y como borrador se utilizó agua. El lugar fue un ambiente con iluminación luz día.

Se aplicó escala hedónica de 5 puntos como se muestra en la Tabla 1, mediante análisis de varianza se identificó las diferencias entre las características sensoriales evaluadas por los panelistas y el grado de aceptación del producto [18].

Análisis estadístico

El análisis ANOVA del diseño experimental de optimización en la formulación de la suspensión se realizó utilizando el software *Statgraphics* versión XVII.II con un nivel de confianza del 95 %.

Los resultados del diseño unifactorial del proceso de secado y del análisis sensorial se compararon mediante un análisis de varianza unidireccional (Minitab. 0.19) con agrupaciones de datos mediante prueba de Tukey, considerando significativa las diferencias para $p<0,05$. Todos los resultados se reportaron como medias ± desviación estándar de mediciones por triplicado de cada tratamiento.

Tabla 1. Escala hedónica de puntuación en el análisis sensorial del producto final en polvo

Valoración numérica	Representación hedónica
1	Me disgusta mucho
2	Me disgusta moderadamente
3	Ni me gusta, ni me disgusta
4	Me gusta moderadamente
5	Me gusta mucho

Fuente: Autores.

Resultados y discusión

Caracterización fisicoquímica del suero lácteo y pulpa de mora

Los resultados obtenidos de las mediciones de las propiedades fisicoquímicas en la pulpa de mora y en el suero lácteo dulce se muestran en la Tabla 2. Los valores reportados fueron el resultado de las mediciones realizadas por triplicado.

Tabla 2. Propiedades fisicoquímicas de pulpa de mora y del suero lácteo dulce

Propiedad	Unidad	Resultados pulpa de mora (media ± SD)	Resultados suero lácteo dulce (media ± SD)
pH	-	2,74 ± 0,04	6,40 ± 0,03
Acidez	%	2,72 ± 0,04	0,35 ± 0,04
Humedad	%	90,92 ± 0,86	-
Antioxidantes	ug/ml	5,49 ± 0,65	-
Polifenoles	ug ácido gálico/g	4,66 ± 0,23	-
Sólidos Solubles	°Brix	8,18 ± 0,23	7,22 ± 0,04
Solidos Totales	%	-	7,90 ± 0,20
Proteína	%	-	1,52 ± 0,35

Fuente: elaboración propia

La mora presentó valores de pH mayormente ácidos, siendo una característica propia de las bayas y frutos rojos. Valores similares han sido reportados por [19] en una suspensión coloidal de pulpa de mora (3,07± 0,01); acorde al valor de pH, se obtuvo alta acidez, tal como lo reportó [20] en su estudio de caracterización de zarzamora secada en lecho fluidizado (2,1± 0,04). Mientras que, el suero lácteo presentó un valor de pH cercano al neutro, propiedad ajustada al tipo de suero dulce, lo cual facilita su uso en formulaciones en combinación con frutos ácidos [21]. Resultados iguales han sido reportados en suero dulce (6,40) según los autores [22]. Se obtuvo valor de acidez moderada, esto debido a que se trabajó con suero fresco esterilizado, evitando de esta manera una fermentación acelerada [23]. Con estos resultados se puede inferir que tanto la acidez como el pH dependen del estado fresco en el que se encuentre el suero, dado que durante el transporte puede iniciar procesos fermentativos [24].

Los resultados en sólidos totales y sólidos solubles fueron similares en el suero lácteo dulce, siendo coherente dado que, en el suero se encuentra gran cantidad de sólidos correspondientes a proteínas solubles, lactosa, minerales y calcio [11]. Esto desde luego, es positivo para el aprovechamiento del suero en productos en polvo principalmente en el factor de rendimiento en el proceso de secado. Por otra parte, se obtuvo un alto valor en proteína respecto al reportado en el estudio de [25], quienes informaron valores menores (0,46 %), en suero utilizado para bebidas funcionales. El contenido de proteína es importante ya que es un componente que aporta al perfil nutricional del producto final en el que se busca incorporar el suero.

En la mora también es característico un alto contenido de humedad, así como lo reporta [20] con un valor de 85,5 %, el cual es cercano al obtenido en esta investigación. Otra propiedad relevante fue el contenido de compuestos bioactivos. En este contexto, el método DPPH se ha utilizado ampliamente, dado a que es un radical libre estable para evaluar la capacidad antioxidante [26]. En un estudio realizado por [27] encontraron valores mayores en capacidad antioxidante en extracto de mora con diferentes solventes (0,25 a 4 mg/mL). Por otra parte, el contenido de polifenoles ha sido determinado en mora de castilla provenientes de la sierra ecuatoriana con un valor de 2,66 mg ácido gálico/g [26]. Estos resultados en compuestos bioactivos proporcionan indicios del potencial nutricional que aporta la mora. Las variaciones en los resultados obtenidos con respecto a los reportados por otros autores se pueden atribuir a factores como la variedad, factores ambientales, la calidad y el estado de madurez la fruta [12].

Formulación de la suspensión a base de suero lácteo, pulpa de mora, maltodextrina e inulina

En la Tabla 3 se presentan los valores medios ± desviación estándar de las variables dependientes: viscosidad, pH y °Brix en función de las variables independientes: fracciones másicas de pulpa de mora, suero lácteo, maltodextrina e inulina. Y la Tabla 4 muestra los resultados del análisis de varianza (ANOVA, por sus siglas en inglés) de las variables dependientes e independientes bajo análisis de efectos principales.

Tabla 3. Diseño experimental para la elaboración de una suspensión y valores de las variables independientes (fracciones másicas de pulpa de mora, suero lácteo, maltodextrina e inulina) y dependientes (viscosidad, pH y °Brix)

	Variables Independientes (fracción másica)				Variables Dependientes		
Corridas	**Pulpa mora**	**Suero lácteo**	**Maltodextrina**	**Inulina**	**Viscosidad (cP)**	**pH**	**°Brix**
1	0,297	0,495	0,148	0,060	816 ± 62,43	3,91± 0,09	25,42±0,12
2	0,410	0,410	0,120	0,060	1080 ± 34,64	3,69±0,02	22,71± 0,82
3	0,353	0,468	0,119	0,060	1013 ± 47,34	3,72± 0,05	22,53± 0,60
4	0,314	0,417	0,209	0,060	996 ± 6,36	3,73±0,08	29,81± 0,51
5	0,418	0,314	0,208	0,060	1737 ± 81,45	3,70± 0,06	31,41± 0,25
6	0,375	0,375	0,190	0,060	1313 ± 14,14	3,63± 0,01	30,22± 0,25
7	0,468	0,354	0,118	0,060	1473 ± 14,15	3,67±0,10	23,52± 0,31
8	0,396	0,396	0,148	0,060	1064 ± 91,25	3,68± 0,02	25,53± 0,15
9	0,431	0,336	0,173	0,060	1657 ± 49,50	3,62±0,01	27,42± 0,12
10	0,396	0,396	0,148	0,060	1193 ± 84,85	3,71± 0,04	26,14± 0,05
11	0,396	0,396	0,148	0,060	1110 ± 81,85	3,65± 0,01	26,42± 0,15
12	0,472	0,376	0,092	0,060	1290 ± 14,14	3,65±0,03	21,53± 0,15
13	0,336	0,431	0,173	0,060	1037 ± 84,85	3,73± 0,06	26,52± 0,10

14	0,376	0,472	0,092	0,060	699 ± 13,44	3,66±0,02	20,12± 0,79
15	0,495	0,297	0,148	0,060	1703 ± 85,05	3,55± 0,01	25,74± 0,51

Fuente: elaboración propia.

Tabla 4. Resultados de análisis ANOVA y la significancia de las variables independientes en función de las variables dependientes

Variables Dependientes	Variables Independientes, efectos principales	*P-value (0,05)*
Viscosidad	Pulpa de mora	0,0017*
	Suero	0,0002*
	Maltodextrina	0,0146*
°Brix	Pulpa de mora	0,0029*
	Suero	0,0004*
	Maltodextrina	0,0001*
pH	Pulpa de mora	0,0631
	Suero	0,0808
	Maltodextrina	0,7079

Fuente: elaboración propia.
*Significativo para *p<0,05*

La viscosidad varió entre 699 ± 13,44 cP y 1737 ± 81,45 cP (Tabla 3). Esta propiedad aumentó cuando mayor fue la proporción de pulpa de mora y maltodextrina. Este comportamiento es consistente con estudios realizado por [28], donde la adición de pectina y carboximetilcelulosa (CMC) incrementó la viscosidad en bebidas a base de permeado de suero hidrolizado enriquecido con pulpa de agraz y uchuva. La propiedad fundamental en la optimización de la formulación de la suspensión fue la viscosidad, ya que es un parámetro crítico que determina la textura, aceptabilidad sensorial y estabilidad de la suspensión.

En productos de alta viscosidad se debe evitar la sedimentación de sólidos para generar una sensación agradable al paladar [28]. Valores altos de viscosidad puede atribuirse a la capacidad de la inulina y la maltodextrina para formar estructuras tridimensionales que retienen agua y aumentan la consistencia de la suspensión. Además, el comportamiento de mayor viscosidad se presentó cuando la formulación incluyó mayor proporción de pulpa de mora, componente que aportó pectinas y fibra soluble que actúan como agentes espesantes naturales [29].

El pH, se mantuvo en un rango ácido (3,58 – 3,69), valores que están directamente relacionados por la presencia de pulpa de mora, debido a su contenido natural de ácidos orgánicos. Valores bajos de pH permiten inducir a la estabilidad microbiológica de la suspensión y contribuir a su perfil organoléptico, reforzando el sabor característico ácido del fruto, siendo compatible con la acidez del suero. Estudios como el de [30] han demostrado que el pH influye significativamente en la recuperación y purificación de glicomacro-péptidos en soluciones de proteínas de suero, lo que indica que es una propiedad importante para tener en cuenta según el aprovechamiento que se le dé a este subproducto.

Por otra parte, los sólidos solubles (°Brix) fluctuaron entre 11,60 y 15,60, aumentando con la incorporación de maltodextrina y pulpa de mora. Este parámetro es relevante dado que incide en la percepción de dulzor, textura y vida útil del producto final, niveles regulados de °Brix ayudan a asegurar una suspensión con características funcionales y sensoriales balanceadas; además, la maltodextrina facilita la fluidez de la suspensión en las paredes del atomizador durante el secado, esto debido a su alto temperatura de transición vítrea [31].

Los resultados del análisis ANOVA con un nivel de confianza del 95 % (Tabla 4) obtenidos en la optimización de la formulación de una suspensión en la que se evaluaron las variables independientes pulpa de mora, suero lácteo dulce y maltodextrina mostraron diferencias significativas en los efectos principales sobre las variables dependientes viscosidad y °Brix. Mientras que no presentó diferencias significativas sobre la variable dependiente pH. Esto evidencia que la variación de los rangos evaluados de cada uno de los componentes presentó efecto sobre la fluidez y solidos totales de la suspensión.

En la Figura 2 se presenta la interacción de las variables concentración de suero y concentración de pulpa de mora respecto al ajuste del valor de deseabilidad (82 %) del diseño experimental de la formulación de la suspensión. En la Tabla 5 se presentan los criterios establecidos en la optimización experimental para la formulación de la suspensión; así como, los valores teóricos predichos por el modelo de 2° orden, los valores experimentales obtenidos a partir de tres réplicas a la condición óptima y el error medio experimental (EMR).

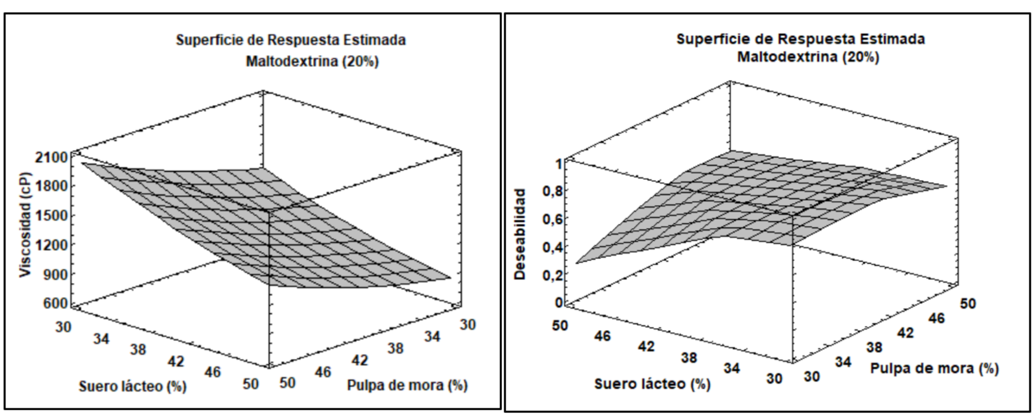

Figura 2. Superficie de respuesta para optimización por múltiples respuestas. A la izquierda variable dependiente viscosidad en función de las variables independientes; pulpa de mora y suero lácteo. A la derecha ajuste del modelo en función de las variables independientes del diseño experimental.

Fuenta: elaboración propia.

El resultado de la optimización por múltiples respuestas y una deseabilidad del 82 % indicó que la formulación óptima de la suspensión debe contener en fracción másica 0,419 de pulpa de mora, 0,319 % de suero lácteo y 0,202 de maltodextrina y 0,060 de inulina. Se identificó que en la formulación optima de la suspensión, la variable independiente suero lácteo tomó el menor nivel en el rango evaluada y la maltodextrina el nivel superior; mientras que la pulpa de fruta tomó un valor medio. Se observó que la propiedad de mayor relevancia fue la viscosidad, identificando que mayor participación de pulpa de mora y menor participación de suero es posible tener valores mayores de viscosidad (Fig. 1). Sin embargo, el factor reológico de la suspensión se determina según la tecnología y las características del equipo de secado [32].

Tabla 5. Comparación de los resultados óptimos de las variables dependientes

Variables Dependientes	Criterio	Óptimo teórico	Óptimo experimental	EMR (%)
Viscosidad (cP)	Maximizar	1630,95	1699 ± 35,55	4,17
pH	Media	3,64	3,54 ± 0,03	2,70
°Brix	Maximizar	31,40	30,65 ± 0,42	2,39

Fuente: Autores

En los resultados obtenidos en la validación de los valores teóricos se identificaron bajos valores de error medio relativo (EMR) (< 5 %), lo que confirma un buen ajuste del modelo de segundo grado y su correlación entre las variables independientes en función de las variables dependientes y a su vez los criterios establecidos para la optimización por múltiples respuestas.

La viscosidad medida experimentalmente en la suspensión óptima presentó una diferencia de 69 cP, con un bajo margen de error (Tabla 5) respecto al valor teórico. En el estudio de [16], quienes estudiaron la microencapsulación de probióticos a través de secado por aspersión, y utilizaron inulina y fructo-oligosacáridos como materiales de pared reportaron que el uso de materiales encapsulantes influye en la viscosidad de las suspensiones y favorecen la eficiencia del proceso de secado. Esto sugiere que la viscosidad establecida en la suspensión óptima es adecuada para asegurar una correcta atomización y formación de partículas durante el proceso de secado.

Caracterización fisicoquímica del producto obtenido del proceso de secado por *spray drying*

Los resultados de la caracterización fisicoquímica del polvo obtenido del diseño unifactorial en el proceso de secado se presentan en la Tabla 6. Aquí la variable independiente fue la temperatura de entrada con 3 niveles 130 °C, 140 °C y 150 °C, en función de las variables dependientes; actividad antioxidante (ug/l), actividad de agua (a_w), solubilidad (%), humectabilidad (g/min) y color (*L* a**, b*).

Tabla 6. Determinación de antioxidantes, actividad de agua, solubilidad, humectabilidad, y color (L*a*b) del polvo prebiótico

Variable Ind. (°C)	Variables dependientes						
	Antioxidantes (ug/g)	Actividad de agua (a_w)	Solubilidad (%)	Humectabilidad (g/min)	Color (L*a*b)		
					L	a	b
130 (1)	$8,92 \pm 0,22^{A}$	$0,36 \pm 0,01^{A}$	$61,91 \pm 2,86^{A}$	$0,08 \pm 0,01^{A}$	$94,06 \pm 1,62^{A}$	$3,03 \pm 1,82^{A}$	$-6,91 \pm 1,87^{A}$
130 (2)	$8,82 \pm 0,28^{A}$	$0,38 \pm 0,02^{A}$	$62,65 \pm 4,27^{A}$	$0,07 \pm 0,01^{A}$	$90,36 \pm 2,01^{A}$	$14,59 \pm 2,31^{A}$	$-8,76 \pm 2,82^{A}$
140 (1)	$7,86 \pm 0,28^{B}$	$0,32 \pm 0,01^{A}$	$49,73 \pm 4,71^{B}$	$0,05 \pm 0,01^{A}$	$89,39 \pm 0,84^{A}$	$17,19 \pm 1,59^{A}$	$-12,40 \pm 0,99^{B}$
140 (2)	$8,04 \pm 0,22^{B}$	$0,33 \pm 0,01^{B}$	$49,65 \pm 2,32^{B}$	$0,05 \pm 0,01^{A}$	$88,61 \pm 1,11^{A}$	$18,25 \pm 1,81^{A}$	$-13,23 \pm 1,26^{B}$
150 (1)	$6,69 \pm 0,25^{C}$	$0,29 \pm 0,01^{B}$	$35,80 \pm 3,35^{C}$	$0,04 \pm 0,01^{A}$	$93,91 \pm 2,37^{A}$	$14,86 \pm 2,03^{A}$	$-9,43 \pm 1,54^{A}$
150 (2)	$6,94 \pm 0,20^{C}$	$0,24 \pm 0,04^{B}$	$41,73 \pm 2,85^{C}$	$0,03 \pm 0,01^{A}$	$93,42 \pm 1,04^{A}$	$10,38 \pm 1,72^{A}$	$-7,63 \pm 1,24^{B}$

Fuente: Autores

*(1): primera muestra, (2): réplica. Las medias que no comparten una letra son significativamente diferentes

En cuanto a la capacidad antioxidante del polvo prebiótico, se observó una reducción progresiva cuando aumentó la temperatura de secado, pasando de 8,92 a 6,69 (ug/g) para las temperaturas de 130 °C y 150 °C respectivamente. Este comportamiento está directamente relacionado con la termodegradación de compuestos fenólicos y flavonoides, los cuales son los principales compuestos que aportan a la capacidad antioxidante. La exposición a temperaturas elevadas conduce al deterioro de los grupos funcionales activos, tales como los radicales hidroxilos fenólicos. En consecuencia, si se desea conservar las propiedades funcionales del producto, se sugiere no exceder temperaturas de 170 °C durante el proceso de secado [20]. En un estudio de los autores [33], quienes determinaron la capacidad antioxidante de mora encapsulada mediante spray-dry usando maltodextrina obtuvieron valores de 91,67 ± 1,53 ug/g.

La actividad de agua (a_w) presentó una disminución significativa respecto al incremento de la temperatura de secado, pasando de 0,38 a 0,24. Este comportamiento se atribuye a la mayor eficiencia en la transferencia de masa durante el proceso de secado por aspersión, ya que temperaturas más elevadas promueven una evaporación acelerada del agua libre contenida en la suspensión. Valores bajos de a_w es altamente favorable, ya que valores menores a 0,3 limitan el crecimiento de microorganismos y reducen reacciones de deterioro, como la oxidación de lípidos y el pardeamiento no enzimático, contribuyendo así a la estabilidad microbiológica y química del producto final [17].

En una investigación donde secaron suspensiones a base de camu-camu y uso de diferentes compuestos encapsulantes; así, con maltodextrina reportaron valores mucho menores de actividad de agua (0,06), y similares en polvos con inulina (0,15) y fructooligosacáridos (0,16) [34]. Esto confirma la efectividad de la maltodextrina como agente encapsulante para mejorar la estabilidad del polvo. Lo que permite mirar que la combinación de maltodextrina e inulina demostró ser funcional para obtener un polvo de baja cantidad de agua microestructural disponible, siendo una propiedad importante para un adecuado almacenamiento y uso posterior en alimentos en polvo.

Respecto a la solubilidad, se evidenció una disminución a temperaturas más altas. A 150 °C se obtuvo menor solubilidad (Tabla 6); mientras que, a 130 °C la solubilidad mejoró, con un valor de 62,28 ± 3,57. Este comportamiento se asocia con la desnaturalización térmica de proteínas y la degradación de azúcares, factores que pueden inducir una fusión superficial de las partículas, dificultando su dispersión en medios acuosos. La solubilidad es una propiedad crítica en polvos funcionales, especialmente para productos instantáneos [17]. Por otra parte, [31] se evaluó la mezcla de inulina y maltodextrina en la obtención de polvos probióticos secados por *spray dry* a una temperatura de 140 °C, el autor obtuvo valores de solubilidad de 87,40 y 80,58 % usando maltodextrina e inulina respectivamente. Con estos resultados se infiere que la maltodextrina permite una mayor solubilidad en los polvos obtenidos mediante *spray dry* en comparación a la inulina.

La propiedad de humectabilidad no presentó diferencia significativa entre los tratamientos evaluados: el polvo presentó baja humectabilidad en agua con valores en un rango entre 0,0828 y 0,0411 g/min. Esta diferencia sugiere que el factor temperatura no tiene efecto sobre esta propiedad funcional. Valores bajos indican fácil aglomeración del polvo reduciendo la interacción con el agua, lo cual dificulta vencer la tensión superficial y por ende afectar una mejor reconstitución [32].

Tabla 7. Resultados de análisis ANOVA y la significancia de las variables independientes en función de las variables dependientes

Variables dependientes	GL	SC Ajust.	MC Ajust.	Valor F	Valor p
Antioxidantes	2	4,238	2,119	121,210	0,001*
Humectabilidad	2	0,009	0,005	4,040	0,141
Solubilidad	2	553,880	276,940	46,520	0,006*
Actividad de agua	2	0,011	0,005	11,100	0,041*
Color L*	2	22,789	11,394	4,700	0,119
Color a*	2	79,940	39,970	1,550	0,345
Color b*	2	29,096	14,548	11,870	0,038*

Fuente: elaboración propia.
*Significativo para $p<0,05$

Finalmente, los parámetros de color también se vieron afectados por la variación térmica durante el proceso de secado. Se identificaron cambios significativos en las coordenadas cromáticas, principalmente en los valores de ***b****, lo que indica variaciones en la tonalidad azul (-b). Este fenómeno se atribuye a la degradación térmica de las antocianinas, compuestos pigmentarios altamente sensibles al calor, lo que influyó en la aparición de todos azulados. En el estudio realizado por [35], en pulpa de *Rubus glaucus benth.*, obtuvieron valores de *L**= 71,16, *a**= 29,30 y *b** = -0,51; la cual fue encapsulada mediante *spray drying* a temperaturas similares a las de esta investigación (120 °C).

La pérdida de compuestos bioactivos no solo reduce la parte visual del producto en polvo, sino que también compromete la funcionalidad antioxidante. [8] mencionaron que el aumento de la temperatura provoca una reducción progresiva del contenido de antocianinas en matrices vegetales, afectando tanto el color como la actividad biológica del producto. En este contexto, la elección de 130 °C como temperatura óptima en el presente estudio se alineó con una mejor preservación de compuestos bioactivos y funcionales del polvo. Este parámetro es fundamental, especialmente si el polvo está destinado a su uso en alimentos instantáneos o bebidas funcionales, donde la capacidad de disolución rápida influye directamente en la aceptación sensorial y funcionalidad del producto.

Análisis sensorial

En la Tabla 8 se muestran los resultados de los valores promedios agrupados en dos grupos de los panelistas no entrenados en la categoría de jóvenes y adultos sobre los atributos sensoriales evaluados en el polvo obtenido. En la Figura 3, se indica la distribución de los resultados en valores promedios de los atributos (olor, color, sabor, textura y aceptación general) utilizando una escala hedónica en escala de 1 a 5.

Tabla 8. Resultados de valores medios agrupados por población jóvenes y adultos en atributos sensoriales evaluados en el producto en polvo

Atributo	Jóvenes ≤30 años (n=18)	Adultos >30 años (n=12)
Olor	3,91 ± 0,53	4,42 ± 0,77
Color	4,31 ± 0,62	4,50 ± 0,52
Sabor	3,93 ± 0,73	3,67 ± 0,63
Textura	4,75 ± 0,65	4,58 ± 0,58
Aceptación general	4,18 ± 0,74	4,17 ± 0,66

Fuente: elaboración propia.

El producto final en polvo presentó una aceptación favorable en ambos grupos de edad. Aunque los adultos destacaron más el olor (4,42 ± 0,77) y color (4,50 ± 0,52), el grupo en la categoría de jóvenes valoraron mejor la textura (4,75 ± 0,65). Esto sugiere que el producto tiene una buena versatilidad sensorial en los dos grupos poblacionales.

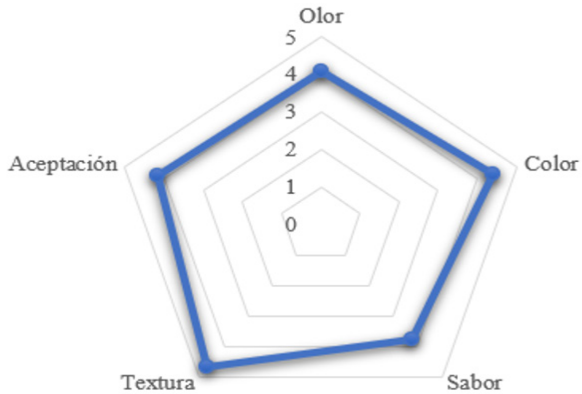

Figura 3. Resultados del panel sensorial en valores promedio, de los atributos (color, olor, sabor, textura y aceptación general del producto).

Fuente: elaboración propia.

Los resultados obtenidos mostraron una tendencia positiva en la aceptación del producto. El análisis de las puntuaciones promedio de los 30 panelistas no entrenados revelaron que la textura fue el atributo mejor valorado, con un promedio de 4,67, seguida del color con 4,40. La valoración global alcanzó un promedio de 4,17, lo que indica una aceptación satisfactoria en una población identificada como potencial consumidora, dado que son personas de las regiones donde se tiene la producción del suero lácteo, lo cual representa un factor importante para la economía del departamento de Nariño, dado que se valorizaría un residuos de bajo aprovechamiento.

Esos resultados sugieren que los procesos de formulación de la suspensión y secado permitieron lograr una textura fina y agradable en el polvo obtenido, así como una apariencia visual atractiva. Aunque el sabor fue el atributo con menor puntuación, sigue estando dentro de un rango aceptable, lo que cual se puede atribuir a las características organolépticas del ácido láctico presente en el suero lácteo [14].

Al comparar estos resultados con el estudio de [36], quienes evaluaron una bebida probiótica a base de suero lácteo y pulpa de mango, se observó una tendencia similar en cuanto a la aceptación sensorial de esta investigación. Los autores reportaron valor promedio de 8,75 en una escala de 1 a 10, reflejando también una alta aceptación del producto. Incluso, el atributo de textura fue el de mejor puntuación, indicando que este atributo presentó un impacto significativo en la aceptación sensorial. El atributo por mejorar fue el sabor, para lo cual se debería avaluar el grado de acidificación del suero, y su posterior fermentación durante el proceso de homogenización y posterior secado.

Los resultados obtenidos respaldan la viabilidad del producto para continuar en fases posteriores de mejora y validación comercial, tal como lo trabajaron los autores [36]. Ya que, el producto en polvo a base de suero lácteo dulce y pulpa de mora presentó alta aceptación sensorial y fue bien recibido por potenciales consumidores

Conclusiones

Los resultados de las propiedades fisicoquímicas del suero lácteo dulce y la pulpa de mora (*Rubus glaucus*) permitieron identificar que ambos aportan compuestos importantes y benéficos al organismo humano. Se destaca el aprovechamiento del aporte proteico (1,52 %) del suero lácteo y de compuestos antioxidantes como los polifenoles (4,66 ug ácido gálico/g) en la pulpa de mora; todos estos son nutrientes relevantes en la gama de productos funcionales.

La formulación óptima de la suspensión prebiótica permitió identificar las proporciones de la mezcla de la suspensión (0,419 en pulpa de mora, 0,319 en suero lácteo, 0,202 en maltodextrina y 0,060 en la inulina), valores que evidencian la posibilidad de incorporar un subproducto poco valorizado en la industria de la cadena láctea en un nuevo producto con valor agregado. Además, se encontró que el uso de inulina y maltodextrina como estabilizadores fueron relevantes para preservar los componentes activos, mantener la suspensión estable y potenciar tanto la facilidad de uso como la uniformidad del producto.

El producto prebiótico en polvo con mejores propiedades funcionales y sensoriales se obtuvo a 130°C de temperatura de aire de entrada en el secado por *spray drying*. A esta temperatura, se consiguió una mejor conservación de los compuestos antioxidantes (8,92 ug ácido gálico/g) y un desempeño positivo en relación con la solubilidad del polvo (62,28 %). Además, el análisis sensorial reveló que el 93 % de los panelistas no entrenados manifestaron su deseo de consumir el producto con una evaluación global de 4,17 (escala de 1 a 5), lo cual indica una aceptación favorable a nivel sensorial y evidenciando que la incorporación de suero lácteo en una nueva matriz alimentaria es una alternativa que le aporta positivamente en marco de la economía circular; puesto que, el nuevo producto contiene nutrientes con potencial funcional de interés para la industria de alimentos.

Financiamiento

La investigación fue financiada por la Universidad Mariana de la ciudad de Pasto – Nariño (Colombia) y con recursos de los autores.

Agradecimientos

Los autores expresan su agradecimiento, a Juliana Oviedo Pantoja y Miguel Ibarra Vallejo, por la colaboración brindada en el desarrollo de las pruebas experimentales, al igual que en la organización y análisis de los resultados.

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DOI: https://doi.org/10.14483/22487638.23958

INVESTIGACIÓN

Tratamiento de aguas residuales cárnicas mediante un sistema de flotación por aire disperso con burbujas de tamaño mediano

Treatment of meat wastewater using a dispersed air flotation system with medium-sized bubbles

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Fecha de Recepción: 28 de julio de 2025 **Fecha de Aceptación:** 22 de diciembre de 2025

Cómo citar: A. D. J. Urrego Cortes, H. C. Oñate Barrasa, and G. Y. Cortés Henao. (2025). Tratamiento de aguas residuales cárnicas mediante un sistema de flotación por aire disperso con burbujas de tamaño mediano. *Tecnura*, 29(86), 36–58. https://doi.org/10.14483/22487638.23958

Abstract

Background: Meat processing industries generate effluents with high pollutant loads, requiring the adoption of efficient treatment technologies that comply with environmental regulations.

Objective: The efficacy of a Dispersed Air Flotation (DAF) system in removing contaminants from meat processing wastewater was investigated, using medium-sized bubbles generated by air.

Methodology: Representative samples were collected from the meat processing plant of the municipality of Agustín Codazzi, located in the department of Cesar, Colombia. Samples were characterized through physicochemical analyses following Standard Methods guidelines, evaluating parameters such as pH, chemical oxygen demand (COD), oils and greases (O&G), turbidity, and temperature. A laboratory-scale pilot DAF system was implemented using a ½-inch diameter Venturi injector to induce the formation of medium-sized bubbles (0.69 mm).

Results: Results revealed a dependence of bubble size on retention time. The optimal configuration for O&G removal (77.9%) and COD removal (74.2%) corresponded to a retention time of twenty minutes, while turbidity removal efficiency of 38.8% was achieved at a retention time of five minutes.

Conclusions: The findings demonstrate that the DAF system, with optimized bubble size and retention time, constitutes an efficient alternative for the treatment of meat industry effluents and for maximizing O&G, COD, and turbidity removal, making its potential application at a larger scale viable.

Funding: Universidad Popular del Cesar (UPC).

***Keywords*:** oils and greases, bubbles, dispersed air flotation, meat processing plant, wastewater

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Resumen

Contexto: las industrias cárnicas generan efluentes con elevadas cargas contaminantes, lo cual exige la adopción de tecnologías de tratamiento eficientes que cumplan con la normativa ambiental.

Objetivo: se investigó la eficacia de un sistema de flotación por aire disperso (*Dispersed Air Flotation*, DAF) en la remoción de contaminantes de aguas residuales cárnicas, con un tamaño mediano de burbujas generadas por aire.

Métodología: se recolectaron muestras representativas de la planta procesadora de cárnicos del municipio de Agustín Codazzi, ubicado en el departamento del Cesar, Colombia. Las muestras fueron caracterizadas mediante análisis fisicoquímicos de acuerdo con los lineamientos del *Standard Methods*, y se evaluaron parámetros como pH, demanda química de oxígeno (DQO), Aceites y Grasas (AyG), turbidez y temperatura. Se implementó un sistema piloto de DAF a escala laboratorio, con el empleo de un inyector Venturi de diámetro ½" para inducir la formación de burbujas de tamaño mediano (0.69 mm).

Resultados: los resultados revelaron una dependencia del tamaño de burbuja con el tiempo de retención. Se encontró que la configuración óptima para la remoción de AyG (77.9 %) y DQO (74.2 %) correspondió a un tiempo de retención de veinte minutos y un tiempo de cinco minutos para la turbidez con una eficiencia de 38.8 %.

Conclusiones: los hallazgos demuestran que el sistema DAF, con la optimización del tamaño de burbuja y del tiempo de retención, constituye una alternativa eficiente para el tratamiento de efluentes industriales cárnicos y para maximizar la remoción de AyG, DQO y turbidez, lo que hace viable su potencial aplicación a mayor escala.

Financiamiento: Universidad Popular del Cesar (UPC).

***Palabras clave*:** aceites y grasas, burbujas, flotación por aire disperso, procesadora de cárnicos, aguas residuales

Introducción

La industria alimentaria, particularmente la del procesamiento de carne, se caracteriza por un elevado consumo de agua en sus procesos productivos y de limpieza [1]. Estas industrias generan aguas residuales con altas cargas contaminantes que, de no recibir un tratamiento adecuado, representan un elevado riesgo para el medio ambiente y la salud pública [2]. La descarga de estos efluentes sin tratamiento en alcantarillas o cuerpos de aguas naturales puede ocasionar diversos daños ambientales, desde obstrucciones en sistemas de tratamiento hasta la destrucción irreversible de ecosistemas [3].

La planta de beneficio animal de Agustín Codazzi, Cesar, Colombia, ha reportado una elevada carga contaminante con parámetros críticos como turbidez, Demanda Química de Oxígeno (DQO), Aceites y Grasas (AyG) en el efluente de sus aguas residuales. Por ello, a pesar de que la planta cuenta con una trampa de grasas para el tratamiento de sus aguas residuales, se debería optar por tecnologías más eficientes para disminuir de manera más efectiva la carga contaminante [4].

Entre los efectos que producen las aguas residuales de origen cárnico se encuentran la formación de películas superficiales de aceites y grasas que pueden ocasionar la aparición de malos olores y enfermedades pues impiden el intercambio gaseoso debido a su lenta biodegradabilidad [5], [6]. En este tipo de aguas residuales, las altas concentraciones de materia orgánica medidas mediante la Demanda Química de Oxígeno (DQO) y la Demanda Bioquímica de Oxígeno (DBO), los Sólidos Suspendidos Totales (SST) y los aceites y grasas (AyG) que al solidificarse pueden provocar obstrucciones en el alcantarillado incrementan el riesgo de desbordamientos de aguas residuales y la exposición de la población a patógenos potencialmente peligrosos [7].

A pesar de la disponibilidad de opciones convencionales para el tratamiento primario de estas aguas residuales, como la flotación por aire disuelto, la flotación electrolítica y el sistema por de flotación por aire disperso (*Dispersed Air Flotation* , DAF), la remoción eficiente de AyG sigue siendo un desafío [8], [9].Estas tecnologías, a pesar de ser utilizadas a gran escala, tienen eficiencias de eliminación que oscilan entre un 50 % y 80 %, lo que no siempre resulta suficiente para garantizar el cumplimiento de las regulaciones más recientes [10]. En el caso de Colombia, el Decreto 0631 de 2015 especifica condiciones estrictas para las descargas, lo cual se traduce en la necesidad de que las industrias apliquen tratamientos más eficientes para evitar consecuencias legales y reducir los efectos adversos en los ecosistemas.

Bajo estas condiciones, es crucial la exploración de alternativas destinadas a mejorar la eficacia de los sistemas de tratamiento actuales. Un enfoque prometedor radica en el control del tamaño de las burbujas empleadas en la etapa de flotación, un parámetro crítico que influye directamente en la eficiencia de la adhesión-separación de la contaminación, como lo demuestran estudios recientes [11], [12], en los cuales se evidencia el uso de tamaños específicos de burbuja y de ciertos dispersores de burbuja para la mejora en la extracción de compuestos orgánicos e inorgánicos, así como la suspensión y separación de residuos. La posibilidad de adaptar los tamaños de las burbujas a la variada composición de las aguas residuales podría demostrar una mayor eficiencia en estos procesos.

El objetivo principal de este proyecto fue la evaluación de la eficiencia de un sistema de flotación por aire disperso en el tratamiento de aguas residuales provenientes de industrias cárnicas, mediante el desarrollo de un sistema piloto capaz de generar burbujas de tamaño mediano. Esto permitió determinar la relación tamaño y tiempo de retención hidráulica para maximizar la remoción de AyG, DQO y turbidez, para mejorar la eficiencia de los tratamientos y reducir el impacto ambiental asociado.

Metodología

En esta sección se describen las diferentes etapas del desarrollo de esta investigación, divididas en tres fases: fase I, recolección y caracterización de las aguas residuales de la industria cárnica; fase II tratamiento de las muestras de agua residual cárnica mediante un DAF con burbuja mediana; fase III, evaluación de la eficiencia de remoción del sistema DAF propuesto.

Fase I. Recolección y caracterización de las aguas residuales

La toma de muestras se realizó en la cajilla de inspección ubicada en el efluente final después de los procesos de producción de la Planta de Beneficio Animal del Matadero Municipal del municipio de Agustín Codazzi en el departamento del Cesar. Las muestras se tomaron y preservaron siguiendo los lineamientos establecidos por la *Guía para el monitoreo de vertimientos, aguas superficiales y subterráneas del IDEAM* y la guía APHA-AWWA-WEF [13]. Se realizó un muestreo de tipo compuesto, tomando unas muestras puntuales de 400 ml cada dos horas la cual se almacenaron en una botella de plástico, para un total diario de dos litros. Para la evaluación de AyG se tomaron tres frascos de vidrio de 300 ml cada uno para cada muestra puntual. La toma de muestras se repitió tres veces cada una en semanas diferentes.

Culminada la recolección de las muestras, se realizó un análisis inicial *in situ* de los parámetros pH, caudal y temperatura; posteriormente se analizaron en el laboratorio los parámetros DQO, turbidez, temperatura, AyG. Los análisis se realizaron según la metodología descrita en *Standard Methods for the Examination of Water and Wastewater*, publicado por la American Public Health Association (APHA), la American Water Works Association (AWWA) y la Water Environment Federation (WEF) [13].

El pH se determinó mediante el método electrométrico (4500-H^+ B) utilizando un potenciómetro previamente calibrado. La DQO se analizó por el método de reflujo cerrado titulométrico (5220 C), basado en la oxidación con dicromato en medio ácido y posterior titulación. La turbidez se midió mediante el método nefelométrico (2130 B) empleando un turbidímetro calibrado. Los AyG se determinaron mediante el método gravimétrico por extracción con solvente (5520 B).

Fase II. Implementación y puesta en marcha de la unidad piloto

Las muestras recolectadas se sometieron a un tratamiento de flotación por aire disperso (DAF) en el laboratorio ambiental de la Universidad Popular del Cesar. El equipo piloto consta de un tanque de flotación circular con capacidad de 30 L, fabricado en acrílico transparente de 8 mm de espesor en posición vertical, con una altura de 1,72 m y un diámetro de 17 cm; su diseño tomó como referencia la celda de James tipo Imhoff-lot y la columna de flotación. Al tanque se le acopló un inyector de burbujas tipo venturi de ½'', encargado de introducir microburbujas de forma descendente al sistema. Asimismo, se instaló una bomba de agua de medio caballo de fuerza (0,5 HP) para garantizar la recirculación del fluido; en dicho proceso, el agua residual se captaba en la parte inferior del tanque y se recirculaba por la parte superior.

Puesta en marcha de la unidad piloto

La puesta en marcha del sistema piloto inició con la activación de la bomba impulsora, que condujo el agua residual a través de una tubería conectada a la parte superior del tanque de flotación. En el extremo de dicha tubería se instaló un dispersor tipo venturi, encargado de generar microburbujas dentro del sistema. El flujo descendente favoreció la interacción y coalescencia burbuja-partícula. Posteriormente, debido a la diferencia de densidades, las burbujas ascienden hacia la superficie arrastrando el material disperso y formando una capa superficial de grasa. El sistema opera recirculando el agua residual de forma continua durante 20 minutos; cada 5 minutos se extrajeron muestras con el fin de evaluar el rendimiento del dispersor de burbujas en función del tiempo.

Caracterización de las burbujas generadas (tamaño, velocidad de ascenso y presión de generación).

Se realizó la medición de algunas características físicas de las burbujas como el tamaño, velocidad y presión de estas. Antes de analizar se tuvieron en cuenta unas consideraciones:

- Se utilizó para este fin agua potable de la llave para una mejor visibilidad de las burbujas en el tanque de flotación.
- Se colocó una cuadrícula de 1 cm x 1 cm en una parte del tanque para poder realizar la respectiva calibración de cada software.
- Se utilizó un celular con su trípode a 40 cm de altura y a 30 cm de distancia del taque de flotación para todas las tomas de fotografía y video.

Caracterización del tamaño de burbujas.

El análisis del tamaño de burbuja se realizó mediante el software *Bubble Analyzer Analyzer* [16], utilizando 100 imágenes por condición experimental, con lo cual se obtuvo el diámetro promedio de las burbujas generadas. La metodología y el procedimiento detallado para el uso del software se desarrollaron siguiendo el protocolo propuesto por Mella [14], ver Anexo 1.

Caracterización de la velocidad de ascenso de las burbujas generadas.

La velocidad de ascenso de las burbujas se determinó mediante el software **Tracker 6.2**, empleado para el análisis de trayectorias y el cálculo de variables cinemáticas a partir de videos. Este software permite calcular datos de posición, velocidad y aceleración de los objetos estudiados [17].

Se utilizó como base la metodología sugerida por la Universidad de Burgos [18] en su manual de nuevas tecnologías para la detección de la trayectoria de objetos. La figura 1 muestra lo que encontraremos al seguir el paso a paso en la utilización del software Tracker 6.2.

Caracterización de la presión de generación de las burbujas.

Para la caracterización de la presión, se instaló un manómetro de presión de 80 psi antes de la implementación del dispersor venturi en el piloto, y de esta manera se midió la presión con que se generó el tamaño de burbujas mediano.

Fase III: evaluación de la eficiencia del prototipo diseñado en el tratamiento de las aguas residuales cárnicas

En esta fase se evaluó la eficiencia del sistema de flotación DAF en la remoción de contaminantes presentes en aguas residuales provenientes de la industria del sector cárnico. El diseño experimental es un diseño factorial mixto con medidas repetidas; este diseño es de carácter longitudinal y no es completamente aleatorizado.

Diseño experimental para la evaluación de la eficiencia del prototipo.

El diseño experimental para la evaluación de la eficiencia del piloto está dado por las siguientes características:

Factores y niveles.

Para evaluar la eficiencia del proceso de flotación, se consideraron dos factores principales:

- **Factor 1: Tamaño de burbuja**
  - Mediano (300 mm - 1000 mm).
- **Factor 2: Tiempo de tratamiento (5 niveles)**
  - Inicial
  - 5 minutos.
  - 10 minutos.
  - 15 minutos.
  - 20 minutos.

Se evaluaron **la eficiencia de remoción de contaminantes de las aguas residuales** cárnicas con burbujas de rango de tamaño mediano.

Variables dependientes

Para cada combinación de tamaño de burbuja y tiempo de tratamiento, se midieron los siguientes parámetros:

- **DQO (% de remoción).**
- **AyG (% de remoción).**
- **Turbidez (% de remoción).**
- **pH medido en cada tiempo.**

El porcentaje de remoción de los contaminantes (% R) se expresa como se muestra en la ecuación 1:

$$\%R = \frac{\left(carga\,contaminante\,de\,entrada - carga\,contaminante\,de\,salida\right)}{Carga\,contaminante\,de\,entrada} * 100 \qquad (1)$$

En la Tabla 1 se exponen los factores y niveles del diseño experimental con sus respectivas repeticiones en cada uno de los tiempos previamente establecidos.

Tabla 1. Factores y niveles del diseño experimental

TIPO DE AGUA	PARÁMETRO	FACTOR 1 (Tamaño de burbujas)	BLOQUE	FACTOR 2 (Tiempo)				
				Inicial	5 min	10 min	15 min	20 min
Aguas residuales de origen cárnico	Parámetro x	Mediana	Bx	Rep 1	Rep 1	Rep 1	Rep 1	Rep 1
				Rep 2	Rep 2	Rep 2	Rep 2	Rep 2
				Rep 3	Rep 3	Rep 3	Rep 3	Rep 3
				Rep 2	Rep 2	Rep 2	Rep 2	Rep 2
				Rep 3	Rep 3	Rep 3	Rep 3	Rep 3

Fuente: elaboración propia.

Aunque en la Tabla 1 no se muestra la medición de pH, este parámetro se midió en cada tiempo de muestreo para evaluar su evolución durante el proceso y analizar si hubo cambios significativos en función de la remoción.

Procedimiento experimental

Se recolectan muestras de aguas residuales directamente en la industria cárnica, en tres días distintos para conformar los bloques experimentales. En cada día de muestreo se recoge 40 L para realizar las pruebas y sus repeticiones internas. Las muestras recolectadas se almacenan en un refrigerador y se dejan a temperatura ambiente antes de cada ensayo.

El sistema DAF opera en modo continuo durante 20 minutos por cada ensayo. Se toman muestras en botellas diferentes en los tiempos 5, 10, 15 y 20 minutos y una muestra inicial que permite evaluar la evolución del tratamiento.

Durante este tiempo, se generan las burbujas del tamaño correspondiente (300 mm – 1000 mm) al tratamiento mediante un sistema controlado. Cada muestra se analiza por triplicado para determinar DQO, AyG, turbidez y pH

El proceso completo en cada tipo de aguas residuales se repitió tres veces, utilizando muestras distintas en cada ocasión. En la Tabla 1, estas repeticiones se presentan en la columna "bloques", correspondiente a tres bloques o repeticiones globales del experimento. Esto permite aumentar la exactitud de los resultados y depuración de los datos erróneos. En resumen, se analizaron 45 muestras: 1 tamaños de burbuja × 5 tiempos × 3 réplicas internas × 3 bloques = 45 muestras.

Análisis estadístico.

Pruebas preliminares

Antes del análisis factorial, se realizaron pruebas para verificar el cumplimiento de los supuestos del análisis de varianza (ANOVA):

- Prueba de normalidad (Kolmogorov-Smirnov): para evaluar si los datos presentan una distribución normal.
- Prueba de homocedasticidad (Test de Barlett o Test de Levene): para verificar si la dispersión de los datos es homogénea entre los grupos.

Los datos que no cumplieron los supuestos de normalidad y homocedasticidad fueron analizados mediante pruebas no paramétricas (Kruskal-Wallis o ANOVA de doble vía), los que sí cumplieron, se analizaron mediante un ANOVA de dos factores para datos paramétricos.

Análisis de efectos principales e interacción

Se realizó un ANOVA factorial de dos vías con bloques aleatorizados el agua residual cárnica, evaluando:

- El efecto del tamaño de burbuja en la eficiencia del tratamiento.
- El efecto del tiempo de tratamiento en la remoción de contaminantes.
- La interacción entre el tamaño de burbuja y el tiempo, determinando si el rendimiento del sistema depende de la combinación de ambos factores.
- Diferencias entre los dos tipos de aguas residuales en términos de remoción de contaminantes.

Para identificar diferencias significativas entre grupos, se aplicaron pruebas de comparaciones múltiples *post hoc* (Dunn) para datos no paramétricos y prueba de Tukey para datos paramétricos.

Resultados

Caracterización fisicoquímica inicial de las aguas residuales

Una vez realizadas las determinaciones de los parámetros fisicoquímicos en las aguas residuales de la industria cárnica, se obtuvieron los valores correspondientes a el caudal, pH, temperatura, DQO, AyG, Turbidez y SST. La Tabla 2 muestra los resultados de estos parámetros en las aguas residuales cárnicas.

Tabla 2. Parámetros de aguas residuales cárnicos iniciales y medidos *in situ*.

Parámetro	Unidad	Máximo	Mínimo	Promedio	[19]	Resolución 0631 de 2015
Caudal	L/s	2,34	2,01	2,19	-	-
Temperatura	º C	29,6	27	28,26	-	-
pH	Unidades de pH	8,9	6,85	7,74	-	-
DQO	Mg O2/L	9984	640	2965	3054,5	450
SST	Mg/L	2063,3	106,7	861,2	3130,5	150
AyG	Mg/L	4574	485	1652,6	2159	20
Turbidez	NTU	593,3	302	410,9	ND	-

Fuente: Autores.

El análisis *in situ* de los parámetros fisicoquímicos del agua residual cárnica (Tabla 2) reveló que no hay una variabilidad significativa en el caudal (2,01 – 2,34 L/s, promedio 2,19 L/s). Esto facilita el control del proceso de flotación al no generarse fluctuaciones grandes en la carga contaminante.

La temperatura del efluente se mantuvo relativamente estable (27,0 – 29,6 °C), con un promedio de 28,26 °C, lo que indica la ausencia de descargas térmicas significativas que pudieran afectar el proceso de tratamiento. Esta misma estabilidad se observa en el pH, cuyo valor promedio se ubica en un rango ligeramente alcalino (7,74). Se registraron variaciones puntuales (6,84 – 8,9); no obstante, el valor promedio se mantiene dentro del rango operativo adecuado para el tratamiento.

La caracterización fisicoquímica inicial del agua residual generada en la industria cárnica evidenció una carga contaminante considerablemente superior a los límites máximos permisibles establecidos en la Resolución 0631 de 2015. La DQO promedio registrada (2965 mg O_2/L) superó en más de seis veces el límite máximo permisible (450 mg/L). De manera similar, la concentración promedio de AyG (1652,6 mg/L, con un valor máximo de 4574 mg/L) excedió ampliamente el nivel máximo permitido (20 mg/L). Los SST también presentaron niveles elevados (promedio: 861,2 mg/L frente al límite de 150 mg/L), al igual que la turbidez (promedio: 410,9 NTU). Al comparar estos resultados con los reportados por Cabrera, se observó que los valores de DQO (3054,5 mg O_2/L) y AyG (2159 mg/L) son ligeramente superiores, pero comparables con los encontrados en el agua residual cárnica del matadero de Agustín Codazzi.

La elevada presencia de materia orgánica puede atribuirse a residuos animales como sangre, tejidos, grasa y otros subproductos, los cuales deben ser tratados adecuadamente antes de su vertimiento. En cuanto a las AyG, concentraciones tan elevadas pueden generar problemas en el sistema de tratamiento, debido a la tendencia de estos compuestos a flotar y formar capas superficiales que interfieren con la oxigenación y el funcionamiento de los procesos biológicos. Los niveles de SST y turbidez registrados indican una alta presencia de partículas finas o coloidales en el agua residual, atribuibles a los residuos orgánicos generados durante las etapas de sacrificio y procesamiento de los animales —sangre, heces, orina, pelos, plumas, grasas y fragmentos de tejido —, que al descomponerse originan partículas finas. La presencia de estos compuestos evidencia la necesidad de implementar un sistema de tratamiento que garantice un efluente final conforme a los estándares de descarga y minimice el impacto ambiental.

Caracterización de las burbujas generadas (tamaño, velocidad de ascenso y presión de generación).

La Tabla 3 presenta un análisis detallado de la parametrización de las burbujas generadas por el sistema implementado, incluyendo el diámetro promedio, la desviación estándar, el rango de tamaños, la velocidad de ascenso promedio con su desviación estándar, la presión de generación requerida, y los resultados del análisis estadístico (pruebas de normalidad de Kolmogórov-Smirnov y Shapiro-Wilk, y las pruebas no paramétricas de Kruskal-Wallis para el tamaño y la velocidad de ascenso).

Tabla 3. Parametrización y análisis estadístico ANOVA de las burbujas.

Tamaño de burbuja	Diámetro (mm) ± DE	Velocidad (mm/s) ± DE	Rango velocidad (mín–máx)	Presión (psi)	Normalidad Krustal wallis Tamaño de Burbuja	Normalidad Krustal wallis Velocidad de la burbuja
Mediana	0,69 ± 0,214 [b]	26,02 ± 5,61 [b]	13,3 – 34,05	35	p < 2.2e-16	p < 1.21e-15

Fuente: elaboración propia

El análisis de los datos revela una clara diferenciación en el diámetro promedio dando como resultado un tamaño de burbuja mediano de (0,69 ± 0,214 mm), lo que confirma la capacidad del sistema para generar y mantener poblaciones de burbujas de un tamaño de manera consistente. La desviación estándar dada puede atribuirse a una dispersión gracias al fenómeno de coalescencia en el dispersor al momento de la generación de las burbujas [15], [19].

Dado que no se cumplió el supuesto de homogeneidad de varianzas para la velocidad de ascenso, el análisis estadístico se realizó mediante pruebas no paramétricas. Los resultados indicaron diferencias estadísticamente significativas tanto en el tamaño de burbuja ($p < 2.2 \times 10^{-16}$) como en la velocidad de ascenso ($p < 1.21 \times 10^{-15}$). Adicionalmente, la relación entre el tamaño de la burbuja, su velocidad de ascenso y la presión de generación evidencia una correlación positiva entre el tamaño promedio de la burbuja y su velocidad de ascenso promedio.

Evaluación de la eficiencia del sistema DAF en el tratamiento de las aguas residuales cárnicas

A continuación, se presenta el análisis estadístico y los resultados de la eficiencia del sistema DAF en términos de remoción de los distintos parámetros evaluados con burbuja mediana. Dado que la disponibilidad de referencias específicas sobre diferentes tamaños de burbuja en la remoción de aguas residuales alimentarias mediante flotación DAF es limitada, se tomaron como referencia estudios sobre sistemas de flotación por aire disuelto que operan con tamaños de burbuja entre 20 µm y 120 µm, así como trabajos sobre el uso de sistemas de flotación en la recuperación y remoción de minerales, crudo y materia orgánica. Los datos detallados correspondientes a los análisis de cada parámetro evaluado se presentan en el Anexo 3.

Evaluación de la eficiencia de la remoción de los parámetros AyG, DQO, Turbidez y pH en el sistema DAF.

En esta sección se analiza en comportamiento general del sistema de flotación DAF en función del tiempo de operación. En este contexto, en la Figura 1 se presenta el gráfico correspondiente a la eficiencia de remoción obtenida para los parámetros AyG, DQO y turbidez.

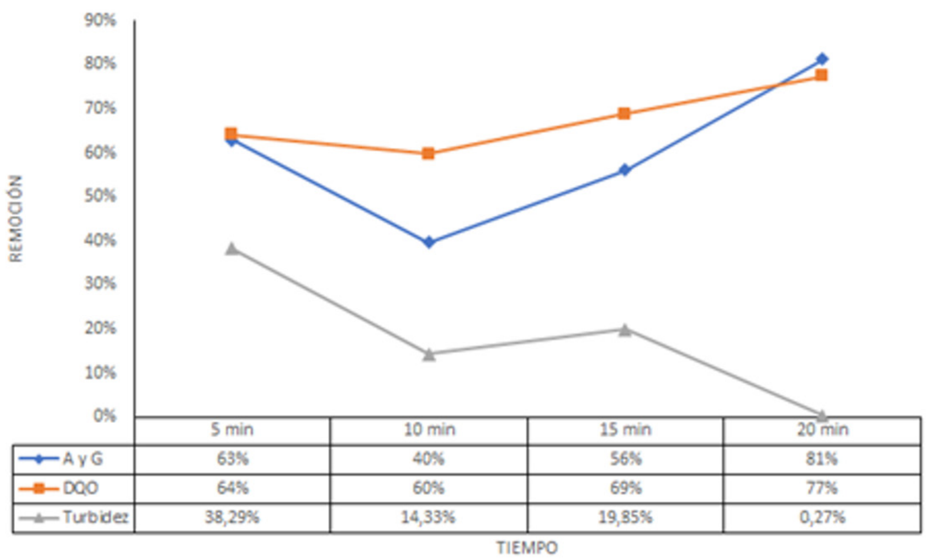

Figura 1. Eficiencia de remoción del sistema DAF en los diferentes parámetros AyG, DQO y Turbidez

Fuente: elaboración propia.

Como se observa en la Figura 1, con respecto al parámetro de AyG, durante los primeros cinco minutos se removieron las partículas de aceites hidrófobas fáciles de arrastrar y flotar; sin embargo, a los minutos 10 y 15 hubo un pequeño bache donde podrían haber quedado partículas más difíciles, como partículas de grasa de menor tamaño, que requieren más tiempo en formar una capa hidrofóbica alrededor de la partícula para ser removidas [23]. Al evaluar el comportamiento del sistema a los 20 minutos, se observó una eficiencia de remoción del 81 %, lo que indica que este tiempo de retención fue el más efectivo, favorecido por una combinación entre un contacto adecuado de burbuja-partícula y una velocidad media de ascenso que optimiza el proceso de flotación [24]. Estos resultados evidencian que el sistema evaluado puede alcanzar eficiencias comparables a las reportadas para otros sistemas de flotación, como la flotación por aire disperso, cuyos valores oscilan entre 80 % y 90 % [5], [25]. A pesar de que la eficiencia de estos dos últimos es un poco mayor a la de nuestro sistema DAF, nuestro proyecto presenta una ventaja sobre aquellos, al requerir menor energía para su funcionamiento, pues no utiliza una bomba adicional para el proceso de presurización, como si la utilizan los sistemas de flotación por aire disuelto.

En relación al parámetro de DQO, durante los primeros 5 minutos de operación se observó un arrastre inicial de materia orgánica; sin embargo, a los 10 minutos se observó una ligera disminución en la eficiencia de remoción. Posteriormente, a los 20 minutos, las burbujas alcanzaron la mayor remoción de DQO, con un valor del 77 %, resultado que podría estar relacionado con un tamaño de burbuja ideal para evitar quedar atrapadas en flujos turbulentos y tener un comportamiento estable y equilibrado, además el área superficial parece ser suficiente para retener partículas orgánicas y coloidales [26]. El nivel de remoción encontrado (77 %), supera algunos valores reportados para sistemas de flotación por aire disuelto aplicados en industrias cárnicas [5], donde se indica que la remoción promedio de DQO en este tipo de sistemas oscila entre el 19 % y el 51 %.

Al analizar la turbidez, se observaron eficiencias de remoción entre 14 % y 38 %, alcanzándose el valor máximo a los cinco minutos. Este comportamiento podría atribuirse a que, en ese intervalo, se presentó una velocidad de ascenso óptima que favoreció la adhesión de las partículas a las burbujas y contribuyó a una mayor estabilidad del sistema, lo que se tradujo en una mejor remoción. Estos resultados concuerdan con lo reportado por Reis [24].

Posteriormente, dicha estabilidad disminuyó debido a fenómenos de turbulencia y coalescencia de las burbujas, que ocasionaron colisiones y desfloculación de las partículas a medida que transcurría el tiempo [27], [28].

La relación de pH a través del tiempo en el proceso de flotación se muestra en la Figura 2**.**

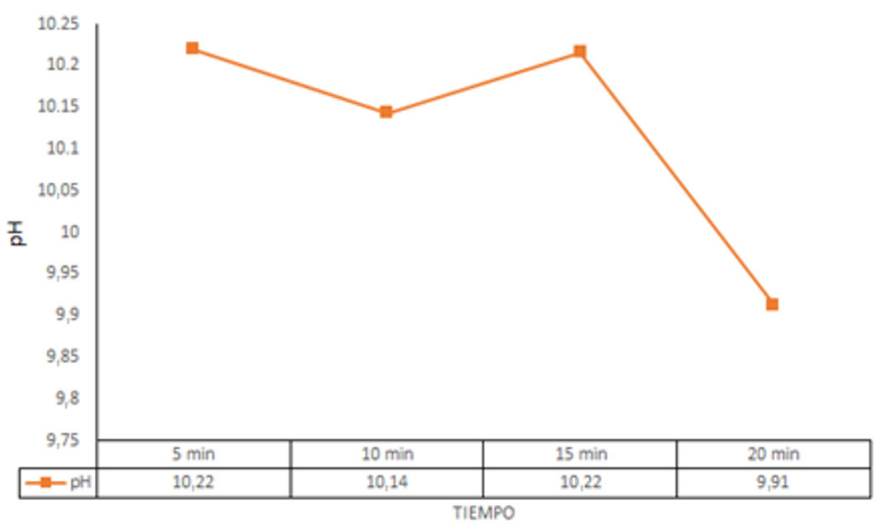

Figura 2. Relación del pH a través del tiempo en el funcionamiento del sistema DAF.

Fuente: elaboración propia.

La Figura 2 muestra la evolución del pH a lo largo del ensayo, con valores que oscilaron entre 9,91 y 10,22. De acuerdo con lo reportado en la literatura los valores esperados para el funcionamiento óptimo de sistemas de flotación van dentro de un pH de 6 hasta un pH de 9,5 [29]. En este caso, el sistema presentó condiciones ligeramente alcalinas que superan los valores óptimos. Comportamiento que puede explicarse por la degradación de compuestos nitrogenados, proteínas y materia orgánica presentes en el agua residual cárnica, especialmente en condiciones anaerobias, se generan productos como amoníaco, que tienen un efecto alcalinizante en el agua residual, elevando así el pH [30]. También esta condición de alcalinidad en el agua residual puede afectar directamente la adhesión de partículas al momento de utilizar un espumante [31].

Diseño experimental

Con el fin de evaluar el efecto del tamaño de burbuja y el tiempo de operación sobre los parámetros de calidad del agua, se realizó un análisis de varianza (ANOVA) de doble vía. La Tabla 4 resume los estadísticos F y los valores de significancia obtenidos para cada variable evaluada.

Tabla 4. Resultados del ANOVA de doble vía para evaluar el efecto del tamaño de burbuja y el tiempo sobre los parámetros DQO, pH, AyG y turbidez.

Parámetro	Factor	F	P	Interacción	Significativo
DQO	Burbuja	4,28	0,0169	No	Sí
DQO	Tiempo	7,44	0,000175		Sí
AYG	Burbuja	2,949	0,0589	No	NO
Turbidez	Burbuja	22,67	<0.001	Sí	Sí
pH	Burbuja	53,17	<0.001	No	Sí

Fuente: Autores

La Tabla 4 presenta para la DQO se observó un efecto estadísticamente significativo tanto del tamaño de burbuja ($F = 4{,}28$; $p = 0{,}0169$) como del tiempo ($F = 7{,}44$; $p = 1{,}75 \times 10^{-4}$). Este comportamiento podría atribuirse a que ambos factores podrían estar influyendo en la eficiencia del sistema, a pesar de que no se evidenció una interacción significativa entre ellos ($p > 0.05$). Los resultados completos del análisis se presentan en el Anexo 2.

En el caso del pH, el tamaño de burbuja mostró un efecto altamente significativo ($F = 53{,}17$; $p = 2{,}86 \times 10^{-16}$), mientras que ni el tiempo ni la interacción burbuja × tiempo presentaron efectos estadísticamente significativos ($p > 0{,}05$), lo que sugiere que las variaciones en este parámetro podrían estar principalmente asociadas al tamaño de burbuja.

Para los parámetros AyG, el efecto del tamaño de burbuja fue cercano al nivel de significancia ($F = 2{,}949$; $p = 0{,}0589$), por lo que no puede considerarse estadísticamente significativo bajo un nivel de $\alpha =$

0,05. Sin embargo, el tiempo sí mostró un efecto significativo ($F = 2{,}821$; $p = 0{,}0451$), lo que podría indicar que el tiempo de retención influye en el comportamiento de este parámetro.

Por otra parte, la turbidez presentó un efecto significativo del tamaño de burbuja ($F = 22{,}67$; $p < 0{,}001$) y una interacción significativa burbuja × tiempo ($F = 5{,}58$; $p < 0{,}001$). Esto sugiere que el efecto del tamaño de burbuja sobre la turbidez podría depender del tiempo de operación, indicando una posible influencia combinada de ambos factores en la eficiencia de remoción.

Comparación de resultados obtenidos con otras tecnologías en el tratamiento de las aguas residuales

Se presenta una comparación entre los resultados obtenidos y los reportados para otras tecnologías de flotación y tratamiento de aguas residuales, tanto a nivel nacional como internacional considerando sus principales ventajas y desventajas. Esta comparativa se muestra en la Tabla 5, donde además de contrastar las ventajas y desventajas se muestran los porcentajes de remoción en distintos parámetros.

Tabla 5. Comparación de los resultados obtenidos con otras tecnologías de flotación y de tratamiento en aguas residuales.

Tecnologías	Eficiencia de remoción (%)	Ventajas	Desventajas	Referencias
Flotación por aire disperso con burbujas variables (Propuesta de esta tesis)	DQO: 77 % AyG: 81 % Turbidez: 38 % pH: 9,91-10,22	-No utiliza coagulante. -El tamaño de burbujas es ajustable para adaptarse al tipo de agua residual. -Gasto energético bajo.	-Requiere un ajuste preciso del tamaño de burbujas y la presión de flujo de agua. -La remoción en turbidez no es muy alta.	[32], [33]
Flotación por aire disuelto en aguas residuales Cárnicas	DQO: 30% AyG: 66-73% Turbidez: 50% pH: 7,41 – 11,63	Eficiencia media-alta dependiendo de las características del agua residual.	-No es posible variar el tamaño de burbujas, permanecen estáticas (20-100 micras).	[4]
Electrocoagulación. aguas residuales de agroindustria.	DQO: 96 % AyG: ND Turbidez:82- 94 % pH: 12,63	-No requiere aditivos químicos, producción de poco lodo.	-Desgaste de electrodos. -Residuos de lodos con residuos metálicos y pH alcalinos.	[34], [35]
Cavitación (hidrodinámica o ultrasónica)	DQO: 30- 90 AyG: ND Turbidez: 65 pH:-	-Remoción media de contaminantes como DQO y turbidez Y contaminantes orgánicos.	Requiere equipos específicos, altos costos	[36], [37], [38]
Trampa de grasas. Industria de embutidos	AyG: 97 % Turbidez: ND pH:6 – 7			[19]

Nota: la sigla ND significa que el parámetro no fue determinado.

Fuente: elaboración propia.

En la Tabla 5 podemos observar que, en comparación con otras tecnologías de flotación, el sistema DAF con burbujas variables desarrollado en esta investigación presenta ventajas importantes frente a métodos convencionales como la flotación por aire disperso. La tecnología de flotación por aire disperso ha sido ampliamente utilizada, en el tratamiento de aguas residuales cárnicas se reportan eficiencias de remoción que alcanzan hasta un 73% en AyG, un 30 % en DQO y un 50% en turbidez [4]. Sin embargo, esta eficiencia media-alta depende de varios factores, como la necesidad de adicionar coagulantes químicos y realizar ajustes de pH, lo cual incrementa tanto los costos operativos como la complejidad del sistema. Además, el tamaño de burbuja en la flotación por aire disperso es fijo (entre 20–100 micras), lo que limita su adaptabilidad y flexibilidad ante diferentes tipos de efluentes.

Por el contrario, el sistema DAF propuesto en esta investigación ha demostrado eficiencias similares o superiores en la remoción de AyG (81%) y una eliminación aceptable de DQO (77 %), sin necesidad de químicos externos ni corrección de pH. Su principal ventaja radica en la posibilidad de ajustar el tamaño de las burbujas, lo que permite adaptar el tratamiento al tipo de agua residual. Esta flexibilidad, sumada a su bajo consumo energético, convierte al DAF en una opción más sostenible. Si bien su eficiencia en la remoción de turbidez (38 %) es menor que en otros procesos, se identifican oportunidades de mejora mediante ajustes operativos o la combinación con otros tratamientos físicos [32], [33].

En el caso de la electrocoagulación, se puede observar altas eficiencias alcanzando hasta un 96% de remoción de DQO y más del 90% en turbidez, gracias a la generación in situ de coagulantes metálicos y burbujas finas de gas [34], [35]. No obstante, este método presenta limitaciones importantes: eleva considerablemente el pH, llegando hasta 12,6, genera lodos o residuos con contenido metálico que requieren un manejo adecuado y supone costo en el desgaste y reemplazo de electrodos. Aunque bien ofrece mejores resultados en la remoción de contaminantes que el sistema DAF, su sostenibilidad a largo plazo y facilidad de operación resultan inferiores.

Otra tecnología emergente es la cavitación hidrodinámica o ultrasónica, que produce burbujas mediante diferencias de presión o sonido de alta frecuencia. Esta técnica ha logrado remociones variables de DQO (30–90%) y de turbidez (~65%) en distintos estudios [36], [37], [38]. Aunque no requiere químicos, su implementación depende de equipos especializados y presenta altos costos energéticos, lo que limita su implementación en contextos con recursos limitados. En comparación, el DAF resulta más accesible, aunque con una eficiencia más moderada en la remoción de compuestos disueltos.

Finalmente, las trampas de grasas son sistemas pasivos de bajo costo, comúnmente utilizados como pretratamientos en cocinas e industrias alimentarias. En versiones mejoradas, como la trampa de grasas con un mayor tiempo de retención y condiciones específicas del agua residual, han mostrado eficiencias más altas en la remoción de AyG hasta de un 97%, especialmente en industrias de embutidos [19]. A pesar de estos avances, estas tecnologías continúan siendo menos versátiles que los sistemas de flotación como el DAF y en la mayoría de ocasiones menos eficientes en la remoción de AyG, particularmente cuando se requiere tratar aguas residuales con cargas orgánicas elevadas o aguas residuales mixtas tanto de origen lácteo como origen cárnico.

En resumen, el análisis evidencia que el sistema DAF con burbujas de tamaño mediano logra un balance favorable entre eficiencia, costo y adaptabilidad, posicionándose como una alternativa prometedora frente a tecnologías más costosas o dependientes de insumos químicos.

Conclusiones

La caracterización inicial de las aguas residuales cárnicas reveló cargas contaminantes significativamente elevadas para DQO, SST, AyG, turbidez y pH, excediendo los límites de la Resolución 0631 de 2015 y subrayó la necesidad de tecnologías de tratamiento más eficientes. Se identificaron características clave en el tipo de efluente como: mayor presencia de sólidos y grasas asociadas a proteínas en aguas residuales cárnicas, grasas con poco emulsificador y de mayor flotabilización.

El sistema DAF demostró la capacidad de generar y controlar el tamaño de burbuja mediano con un diámetro promedio de 0,69 mm, a una presión de generación de 35 psi confirmando la relación entre la presión aplicada y el tamaño de burbuja según la teoría de fragmentación de gas. A pesar de observaciones de turbulencias internas momentáneas, el sistema exhibió una estabilidad operativa general, sugiriendo su potencial para escalabilidad industrial.

La dinámica de las burbujas evidenció una correlación positiva entre el tamaño y la velocidad de ascenso de las burbujas la cual fue en promedio de: 26,0 mm/s, un factor crucial que influye en el tiempo de contacto con los contaminantes y, por ende, en la eficiencia de separación. El tiempo de retención (5-20 minutos) se confirmó como un parámetro operativo determinante en la interacción burbuja-partícula.

En el tratamiento de aguas residuales cárnicas, el mejor resultado para AyG (81 %) se obtuvo con burbujas medianas a 20 minutos, lo que sugiere una influencia de la naturaleza de los lípidos en este caso más solidificados y con una flotabilidad importante.

La remoción de DQO fue de 77% a un tiempo de retención de 20 minutos indicando que los compuestos orgánicos más complejos de las aguas residuales cárnicas requieren un mayor tiempo de contacto. La turbidez se removió más eficientemente en un tiempo de retención hidráulico de 5 minutos con un porcentaje de remoción de 38,8% lo que podría estar relacionado con las diferencias en el tamaño y la buena sedimentabilidad de lo sólidos en aguas residuales cárnicas. El pH se mantuvo un poco alcalinos (9,91-10,22) pero sin afectar significativamente la eficiencia del tratamiento.

Además de validar la eficiencia técnica del sistema DAF, se realizó una comparación con otras tecnologías empleadas en el tratamiento de aguas residuales alimentarias, como la flotación por aire disuelto, la electrocoagulación, la cavitación y las trampas de grasas. Si bien tecnologías como la electrocoagulación y la flotación por aire disperso han demostrado remociones elevadas de AyG, DQO y turbidez, sus altos costos operativos, el uso intensivo de insumos químicos y la generación de residuos secundarios representan desventajas importantes. En cambio, en esta investigación se demuestra potencialmente la adaptabilidad del sistema DAF para el tratamiento de aguas residuales industriales como una alternativa más flexible, económica y sostenible, con una eficiencia que varía en función del tipo de agua, el tamaño de burbuja y el tiempo de retención. En comparación con otras tecnologías, desde una perspectiva preliminar, se resalta su simplicidad, estabilidad operativa y buenos resultados en remoción de AyG y DQO que lo sugiere que podría constituir una solución prometedora para ser aplicada a mayor escala en entornos industriales.

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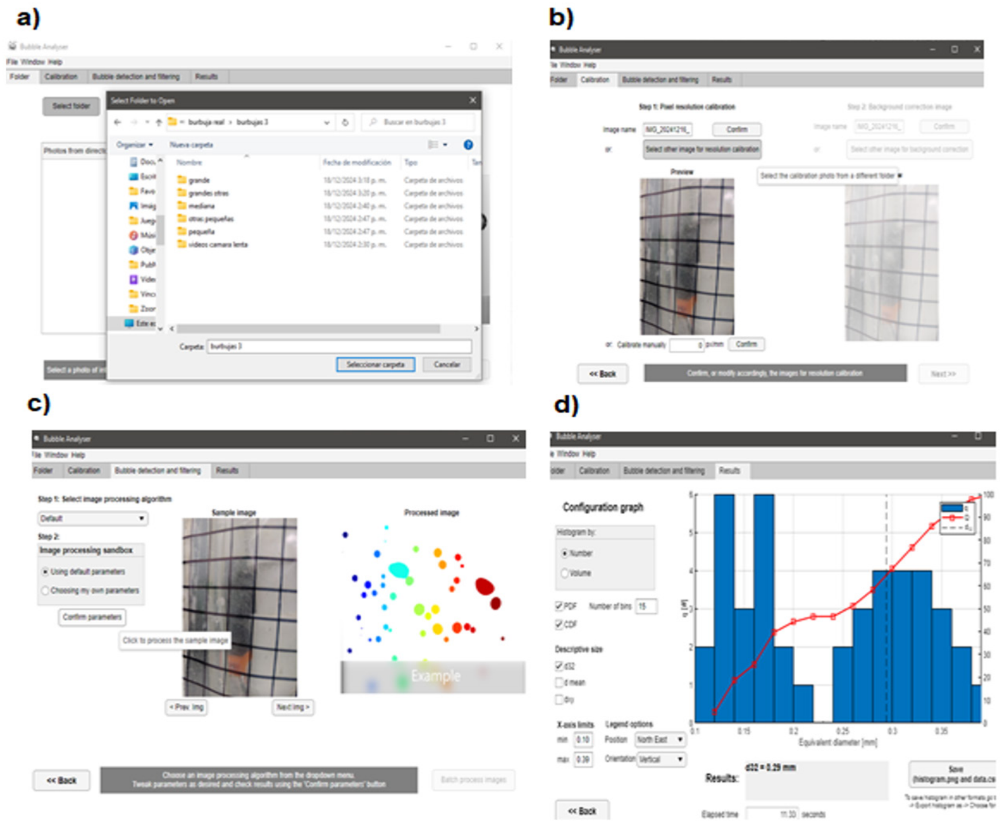
Anexos

Anexo 1. Paso a paso para la obtención del tamaño de burbujas.

Metodología de Análisis de Burbujas con Bubble Analyzer:



Nota: a) Directorio raíz Bubble Analyzer, b) Calibración, c) Confirmación de Parámetros, d) Procesamiento de Imágenes. Tomado del Software Bubble Analyze

Fuente: Autores

Lo primero es abrir el software y elegir el directorio raíz de donde se extraerán las imágenes tomadas a alas burbujas, (a), este directorio debe contener 100 imágenes con el fin de que el software calculé la mediana de las intensidades de cada pixel y así detectar la profundidad y el cálculo espacial. A continuación, se calibra el software subiendo una de las 100 fotos anteriormente tomadas y se seleccionan dos puntos en la foto que estén a 1 cm de distancia, (b). Luego se selecciona el botón siguiente y se da click en el botón confirmar parámetros dejando los parámetros por defecto que trae el software, (c). El siguiente paso es dar click en el botón procesar imágenes y el software automáticamente mide cada una de las burbujas tomadas en las fotografías y saca un promedio de su diámetro y nos arroja el valor exacto. (d)

Anexo 2 ANOVA de cada uno de los parámetros evaluados en las aguas residuales cárnicas en relación al tamaño de burbuja

Análisis de Varianza (ANOVA de doble vía para datos no paramétricos) para la DQO, tamaños de burbuja respecto al tiempo y el test pos hoc de Dunn.

Tipo de análisis	Df	F	Value	Pr(>F)	Test post hoc de Dunn
Anova	Burbuja[b]	85	4,28284	1,69E-02	
	Tiempo[b]	85	7,44E+00	1,75E-04	
	burbuja:tiempo[a]	85	0,96262	0,45554602	
	Burbuja Mediana 20 min		-	-	0,0031 – 0,0048

Análisis de Varianza (ANOVA de doble vía para datos paramétricos) para los AyG, tamaños de burbuja respecto al tiempo y la prueba post hoc de Tuckey.

Tipo de análisis	Df	Sq	F value	Pr(>F)	Test post hoc de Tukey
Anova	Burbuja[b]	1,86E+03	2,949	0,0589	-
	Tiempo[b]	1,78E+03	2,821	0,0451	-
	burbuja:tiempo[a]	1,17E+03	1,861	0,0998	-
	Burbuja Mediana 20 mint		-	-	0,0489
			-	-	> 0,05

Análisis de Varianza (ANOVA de doble vía para datos paramétricos) para la Turbidez, tamaños de burbuja respecto al tiempo y el post test de Tukey.

Tipo de análisis	Df	Sq	F value	Pr(>F)	Test post hoc de Tuckey Diferencia
Anova	Burbuja[b]	14090,2	22,67	0,000	
	Tiempo[b]	931,6	1,00	0,397	
	burbuja:tiempo[a]	10409,6	5,58	0,000	
	Mediana 5 mint		-	-	+58,82
	Mediana 5 mint		-	-	0,0000029
	Mediana 10 min				+33,50

Análisis de Varianza (ANOVA de doble vía para datos no paramétricos) para el pH, tamaños de burbuja respecto al tiempo.

Df	Df.res	F	Value	Pr(>F)
Burbuja[b]	2	96	53,173444	2,86E-16
Tiempo[a]	3	96	0,087783	0,96659
burbuja:tiempo[a]	6	96	0,15297	0,98805

Anexo 3 Resultados de los análisis de los diferentes parámetros estudiados con sus valores máximos, mínimos y promedio.

En la siguiente tabla se muestran los resultados de los análisis del agua residual para cada uno de los intervalos de tiempo a la salida del sistema de flotación piloto utilizado,

	DQO *(mg O2/L)*		
	Máximo	Mínimo	Promedio
Inicial	9984	640	3088
5 min	2880	320	888
10 min	2240	320	1244
15 min	1728	320	960
20 min	1600	320	696
	AyG *(mg/L)*		
	Máximo	Mínimo	Promedio
Inicial	4574	1390	2455
5 min	2210	260	913
10 min	2230	220	1482
15 min	2992	296	1079
20 min	1075	240	537
	Turbidez *(NTU)*		
	Máximo	Mínimo	Promedio
Inicial	612	371	492
5 min	406	206	303
10 min	601	245	421
15 min	435	336	394
20 min	722	278	490
	pH *(Unidades de pH)*		
	Máximo	Mínimo	Promedio
Inicial	11,59	7,86	10,36
5 min	11,74	7,68	10,22
10 min	11,66	7,48	10,14
15 min	11,07	7,98	10,22
20 min	11,55	7,42	9,91

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https://revistas.udistrital.edu.co/ojs/index.php/Tecnura/issue/view/1277

DOI: https://doi.org/10.14483/22487638.24061

INVESTIGACIÓN

Cluster analysis for the prevention of hospital readmission of diabetic patients

Análisis de clústeres para la prevención del reingreso hospitalario de pacientes diabéticos

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Fecha de Recepción: 28 de agosto de 2025 **Fecha de Aceptación:** 13 de noviembre de 2025

Cómo citar: Villanueva-Rueda, C.G; Chávez-Bosquez, O; Hernández-Ocaña, B; and Hernández Torruco, J. (2025). Análisis de clústeres para la prevención del reingreso hospitalario de pacientes diabéticos. *Tecnura*, 29(86), 59–74. https://doi.org/10.14483/22487638.24061

Abstract

Objective: Hospital readmission in diabetic patients represents a significant challenge for both healthcare systems and patients' quality of life. That is why the main objective of this work is to identify common patterns associated with a higher risk of readmission.

Methodology: This study presents a clustering analysis applied to a clinical dataset of diabetic patients who were readmitted to hospitals across 130 medical institutions in the United States. The analysis employs unsupervised clustering algorithms, such as k-means and PAM, to segment patients based on their clinical and demographic characteristics . The study also evaluates different feature selection methods, identifying Simulated Annealing (SA)as the most effective for selecting optimal subsets of variables.

Results: Recurring factors such as length of hospital stay, associated medical conditions, and types of treatment received, significantly influence the probability of readmission.

Conclusions: The clustering results provide valuable insights to guide the development of personalized intervention strategies aimed at reducing hospital readmission rates among diabetic patients.

***Keywords*:** clustering analysis, hospital readmission, diabetes, machine learning, feature selection.

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Resumen

Objetivo: El reingreso hospitalario en pacientes con diabetes representa un reto significativo tanto para los sistemas de salud como para la calidad de vida del paciente. El objetivo principal de este trabajo es identificar patrones comunes asociados a un mayor riesgo de reingreso.

Métodología: Este estudio presenta un análisis de conglomerados (clusters) aplicado a un conjunto de datos clínicos de pacientes con diabetes que fueron reingresados en hospitales de 130 instituciones médicas en Estados Unidos. El análisis emplea algoritmos de conglomerados no supervisados, como k-means y PAM, con el fin de segmentar a los pacientes según sus características clínicas y demográficas. Este estudio también evalúa diferentes métodos de selección de características, identificando el Recocido Simulado (Simulated Annealing) como el más efectivo para seleccionar subconjuntos óptimos de variables.

Resultados: Factores recurrentes, tales como: duración de la estancia hospitalaria, afecciones médicas asociadas y los tipos de tratamiento recibido, influyen significativamente en la probabilidad de reingreso.

Conclusiones: Los resultados del conglomerado proporcionan información valiosa para guiar el desarrollo de intervenciones personalizadas dirigidas a reducir las tasas de reingreso hospitalario en pacientes con diabetes.

Palabras clave: análisis de agrupamiento, reingreso hospitalario, diabetes, aprendizaje automático, selección de características.

1. Introduction

Diabetes is one of the most prevalent chronic diseases worldwide. According to the Interna- tional Diabetes Federation (IDF) (1), 537 million people between the ages of 20 and 79 live with this condition. An alarming increase in the prevalence of this disease is projected, estimating that by the year 2046, around 784 million people could be affected—representing a 46 % increase compared to 2019 (2). This growth presents a significant challenge for healthcare systems, not only in terms of diagnosis and treatment, but also in managing complications and recurrent hospital readmissions.

Indeed, hospital readmissions are a key indicator of the quality of medical services, as they reflect the effectiveness of clinical management, and the patient's ability to stabilize outside the hospital setting. In the context of diabetes, multiple factors, including the type of treatment received, length of hospital stay, and the presence of comorbidities, considerably influence the likelihood of readmission (3). Reducing these readmissions not only decreases costs for healthcare systems but also improves patients' quality of life.

Given the complex and heterogeneous nature of clinical data, the use of machine learning techniques has become an essential tool for extracting meaningful patterns from large volumes of medical information. Although supervised models have been widely applied to predict readmissions, they depend on prelabeled data and may limit the exploration of hidden relationships between variables. In contrast, unsupervised methods, such as clustering algorithms, allow identifying subpopulations of patients with similar characteristics without requiring predefined output information, facilitating hypothesis generation and the comprehension of underlying factors associated with readmission risk.

In this study, *k*-means and Partitioning Around Medoids (PAM) algorithms were applied to a clinical dataset of diabetic patients to detect homogeneous groups, according to their clinical and demographic characteristics. To improve cluster stability and quality, an optimization stage using Simulated annealing, a metaheuristic technique, was incorporated. This approach allowed for better centroid convergence and lower sensitivity to initial conditions. The results showed that the Simulated Annealing-based approach provided the best outcomes, in terms of cluster cohesion and separation, demonstrating its effectiveness in segmenting patients within complex clinical contexts.

Along these lines, this work aims at contributing to more interpretable and adaptive analytical models, allowing healthcare professionals to better understand the diversity of profiles among diabetic patients, and to design personalized strategies accordingly.

2. Related work

Several studies have addressed hospital readmission prediction in diabetic patients using machine learning techniques. One of the most relevant works is titled “Impact of HbA1c Measurement on Hospital Readmission Rates in Patients with Diabetes”, which analyzed more than 100,000 clinical records from 130 hospitals in the United States. This means it employed the same dataset than us. In this study, supervised models such as decision trees, logistic regression, and neural networks were applied to estimate the probability of hospital readmission, demonstrating the relevance of factors such as length of stay, glycemic control, and comorbidities (4).

However, supervised models present limitations as they rely on predefined labels and fail to capture latent structures in data. To overcome this issue, further recent research has incorporated unsupervised methods such as clustering algorithms: “Unsupervised Learning for Diabetes Subgroup Identification Based on Clinical Features and Glycemic Control”. This work applied the *k*-means algorithm to group type 2 diabetic patients according to clinical and demo- graphic variables. The authors identified patterns associated with glycemic control levels and pharmacological treatment, enabling the definition of subgroups with different complication risks (5).

Similarly, the work “Enhanced Clinical Interpretation of Diabetes Clustering via PAM and PCA Integration” combined Partitioning Around Medoids (PAM) with Principal Component Analysis (PCA) to improve the interpretability of the resulting clusters. The results showed that PAM demonstrated greater robustness to outliers and revealed clinically coherent profiles consistent with medical practice (6).

Finally, "Optimization of Medical Data Clustering Using Simulated annealing" demonstrates that integrating optimization metaheuristics, such as Simulated annealing, significantly improves intra-cluster cohesion and inter-cluster separation, in contrast to *k*-means and PAM. This hybrid approach achieved more stable solutions with lower sensitivity to initial conditions (7). These studies highlight the effectiveness of unsupervised methods and metaheuristics in exploring complex clinical data, facilitating patient stratification, and contributing to personalized diabetes treatment.

3. Materials and Methods

3.1 Dataset

This study uses the "Diabetes 130-US Hospitals for Years 1999–2008" dataset (8) from the UC Irvine Machine Learning Repository. The dataset includes data from 130 U.S. hospitals on diabetic patients who experienced hospital or outpatient readmission. It consists of 50 variables and 101,766 instances, with 33 categorical and 17 numerical variables.

For this study, a sample of 5,000 instances was extracted to perform clustering analyses using different algorithms, whose results are discussed in later sections. The original dataset includes 50 variables and 101,766 instances of hospitalized diabetic patients between 1999 and 2008. From these, 17 variables are numerical and 33 categorical. Table 1 summarizes the main numerical variables.

Table 1. Statistical Description of Numeric Variables

Variable	Min	Max	Mean	Std. Dev
time_in_hospital	1	14	4.39	2.47
num_lab_procedures	1	132	43.09	19.67
num_procedures	0	6	1.33	1.70
num_medications	1	81	16.02	8.12
number_outpatient	0	42	0.37	1.29
number_emergency	0	76	0.19	0.86
number_inpatient	0	21	0.10	0.64
number_diagnoses	1	9	7.42	1.35

4. Evaluation and Validation metrics

The evaluation of the results obtained through clustering algorithms requires the use of specific metrics that allow for quantifying the segmentation quality performed. A metric can be defined as a mathematical function used to assess similarity, cohesion, or separation among the grouped elements, depending on the analysis approach and the type of data (9). These metrics are fundamental for comparing the effectiveness of different clustering models.

4.1 Elbow Method

One of the most commonly used techniques to determine the optimal number of clusters is the Elbow method. This technique is based on analyzing the total sum of squared errors (SSE) for different values of *k*, which represents the number of clusters. When plotting the SSE values against *k*, a progressive decrease is typically observed until a point where the improvement becomes marginal. This inflection point is interpreted as the optimal number of clusters, and it is known as the "elbow" of the graph. This metric is especially useful for centroid-based algorithms such as *k*-means, as it provides a visual way to balance between model accuracy and complexity (10).

As shown in Fig. 1, the Elbow method analysis suggests that the optimal value of *k* for this dataset lies within the range of 2 to 5. Starting from *k* = 5, the reduction in the Within- cluster sum of squares (WCSS) becomes marginal, indicating little improvement in cluster compactness. This suggests that increasing the number of clusters beyond this point would not provide substantial benefits to the model and could result in unnecessary oversegmentation.

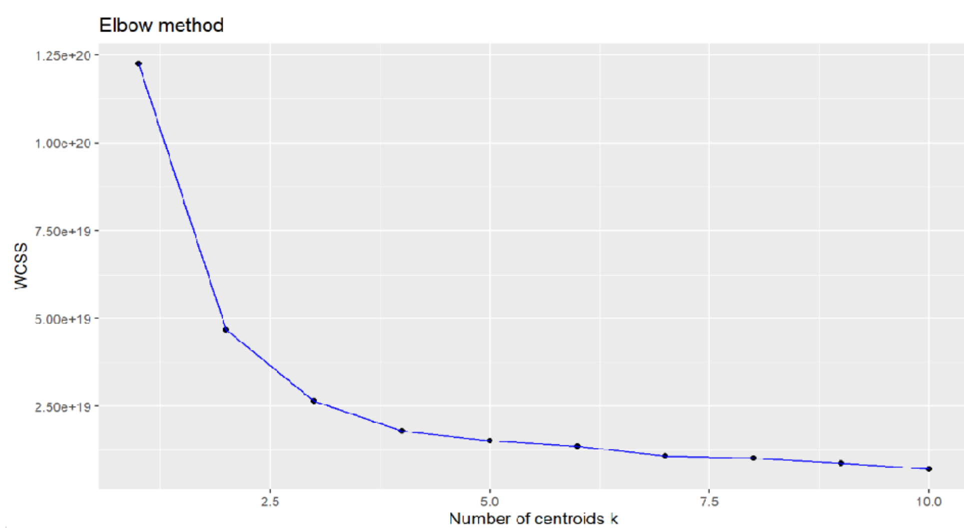


Figure 1. Elbow method for determining the Optimal number of centroids

WCSS (Within-Cluster Sum of Squares) is a metric that measures the sum of the squared distances from each data point to its corresponding centroid within a cluster. In other words, it is a measure of cluster compactness. The goal of the *k*-means algorithm is to minimize this value in order to achieve the most compact clusters as much as possible.

The formula to calculate WCSS is produced as follows:

$$WCSS = \sum_{k=1}^{K} \sum_{x \in C_k} \left\| x - \mu_k \right\|^2$$

Where:

- K: number of clusters.
- C_k: representa el clústercluster k. ▪ x: data point in cluster k.
- μ_k: centroid of cluster k.
- $||x - \mu_k||^2$: squared Euclidean distance between the point x and its centroid.

4.2 Silhouette

The silhouette coefficient is another widely used metric for evaluating clustering quality. This measure combines the concepts of cohesion (how close the points are within the same cluster) and separation (how far the points are from other clusters). The silhouette coefficient ranges from -1 to 1, where a value close to 1 indicates that the instances are well clustered, while values close to 0 or negative suggest incorrect or ambiguous assignments.

The silhouette coefficient provides an overall view of clustering effectiveness and can also be used to determine the appropriate number of clusters by evaluating the average silhouette score across different partitions (11).

5. Data Analysis

Exploratory Data Analysis (EDA) represents a fundamental stage in the development of predictive models. Through statistical techniques and graphical visualization, a deep understanding of the dataset's characteristics is achieved, allowing for the identification of patterns, detection of anomalies, and evaluation of relationships between variables. This prior understanding is essential for performing proper preprocessing, thereby optimizing the performance and interpretability of subsequent models.

5.1 Data Visualization

Data visualization is a powerful tool for EDA, facilitating the interpretation and detection of potential issues in the dataset. The most commonly used techniques include:

- **Histograms:** Allow for the analysis of the distribution of numerical variables, identifying skewness, multimodality, and possible deviations from a normal distribution.

- **Boxplots:** Useful for identifying outliers and evaluating data dispersion in relation to quartiles.

- **Bar Charts:** Used to represent the frequency of categorical variables, providing information about class or category distribution.

- **Scatter Plots:** Allow the evaluation of relationships between two variables, identifying linear or nonlinear patterns that could influence predictive modeling.

Below is a visual exploration of the dataset using various visualization techniques that help identify patterns, distributions, and potential anomalies in the variables. The following images illustrate these graphical representations, highlighting the structure and behavior of the data, thus facilitating interpretation and analysis.

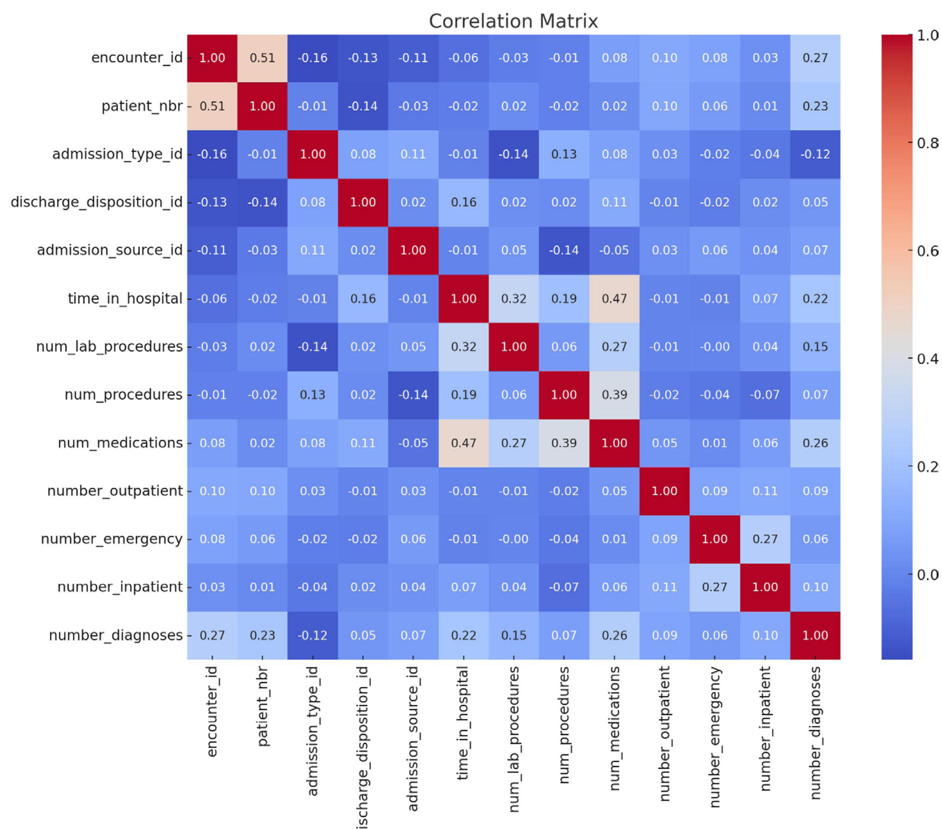
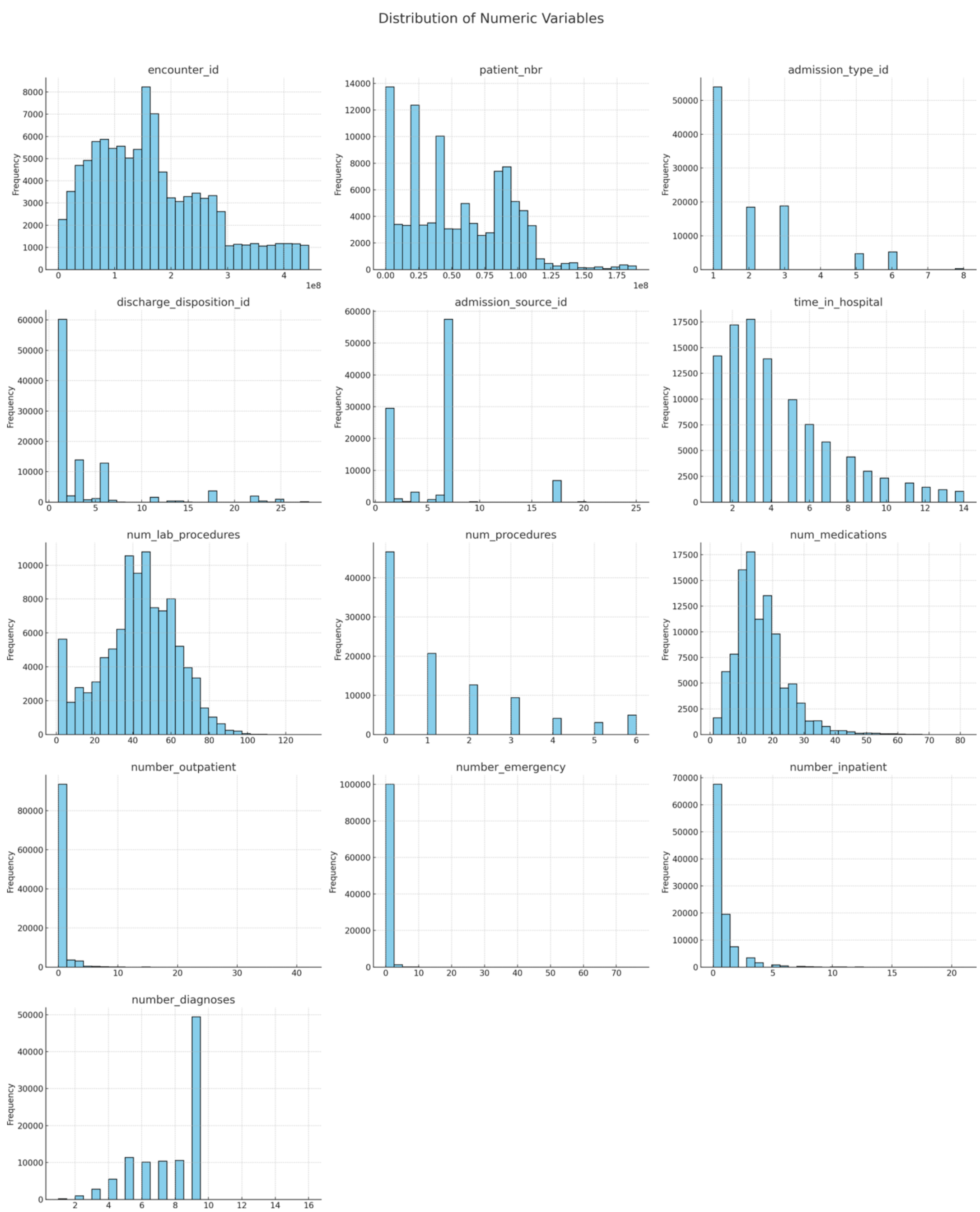


Figure 2. Correlation matrix of numeric variables

In Figure 2, the correlation matrix of the variables selected for analysis is shown. This representation allows the identification of linear relationships between numerical variables, facilitating the detection of collinearities that could affect the performance of predictive models. High positive values (close to 1) indicate a strong direct correlation, while negative values reflect an inverse relationship.

The matrix highlights some significant correlations, such as those between encounter_id and patient_nbr, which may suggest a dependency between these variables in thehospital records. On the other hand, the variable num_medications shows a moderate correlation with num_procedures, indicating a possible pattern in the clinical management of patients. Additionally, variables like time_in_hospital and num_lab_procedures present a positive correlation, which could reflect an increase in laboratory tests as the hospital stay lengthens.

Figure 3. Histograms of numeric variables



In Figure 3, the histograms of the selected numerical variables for analysis are presented. This visualization allows for the observation of data distributions and the detection of potential skewness, outliers, and asymmetries in each variable.

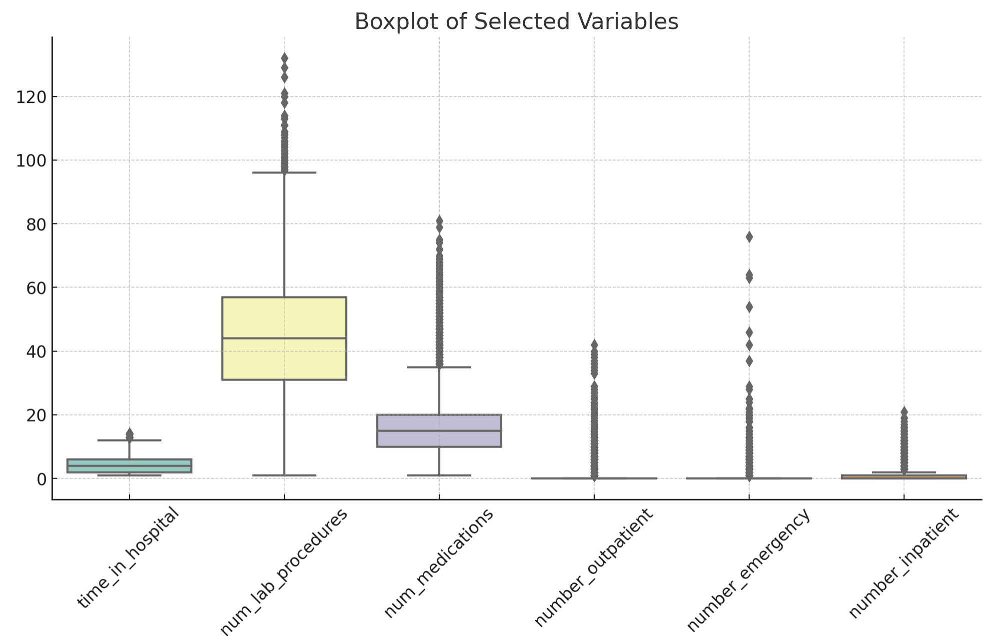


Figure 4. Boxplots for detecting outliers

Comparatively, the histograms reveal distinctive behaviors across variables. For example, variables such as time_in_hospital and num_lab_procedures exhibit slightly skewed distributions, suggesting a higher concentration within specific intervals. Additionally, the variable number_emergency shows a left-skewed distribution, indicating that most patients had few recorded emergencies, while a smaller number presented exceptionally high values.

In Figure 4, the boxplots of the selected variables for analysis are shown. This graphical re- presentation allows for identifying the dispersion of the data, as well as the presence of outliers in each variable. These boxplots reveal notable differences in data variability. For example, the variable num_lab_procedures exhibits a wider interquartile range compared to the others, indicating greater dispersion in the number of laboratory procedures performed. In contrast, the variable time_in_hospital shows a tighter concentration around its central values, even when several outliers stand out above the 75th percentile.

6. Data Preprocessing

After visualizing the data, we observed the presence of missing values represented by ques- tion marks. Therefore, when loading our dataset, we specified that values containing question marks should be replaced with NA, as this is recognized by the R programming language. Similarly, we noted that these missing values were numerical.

Table 2. Table of variables with missing data

Variable Name	Number of Records	Missing Values
weight	101766	98569
payer.code	101766	40256
medical.specialty	101766	49949

As shown in Table 2, the variable weight contains 98,569 missing values out of a total of 101,766 instances, which accounts for more than 80 % missing data. Likewise, the other variables also exceed 20 % of missing data (12). Due to the high proportion of missing values, we chose to remove these variables, resulting in a total of 47 variables remaining for our model.

We found that 33 of the variables were categorical, so it was necessary to transform them from categorical to numerical, as it is essential for modeling that the data be numeric.

Table 3 presents the variables that were excluded from the analysis, resulting in a total of 42 variables selected for experimental testing. This reduction was carried out with the purpose of optimizing model performance and mitigating possible effects of multicollinearity or redundancy in the dataset.

Table 3. Removed variables

Removed Variables
`Encounter_id Patient_nbr Weight Admission_type_id Discharge_disposition_id Payer_code Medical_specialty Num_medications`

7. Modeling

7.1 *K*-means

The *k*-means algorithm is a clustering technique that partitions a dataset into K distinct groups by minimizing intra-cluster variation and maximizing inter-cluster variation. This method is especially useful in applications such as customer segmentation, image compression, and pattern detection in unlabeled data (13).

7.2 PAM

The Partitioning Around Medoids (PAM) algorithm is a clustering technique that, unlike *k*-means, uses actual objects from the dataset as the centers of clusters, called medoids. This makes it more robust to outliers and allows it to work with arbitrary dissimilarity metrics (14).

7.3 FSelector

Feature selection is a crucial process for reducing data dimensionality and improving the efficiency of machine learning models (15). The FSelector library in R provides several techni- ques for this purpo- se, including:

- **Chi-square:** Evaluates the independence between each feature and the target variable, making it useful for categorical data.
- **Information Gain:** Measures the reduction in entropy when the value of a feature is known, favoring those that provide the most information about the target variable.
- **Relief:** Estimates the relevance of features by considering the difference between nearby instances of different classes.
- **Random Forest Importance:** Uses Random forest models to assess each feature's contribution to prediction, identifying the most influential ones.
- **CFS (Correlation-based Feature Selection):** Selects subsets of features that are highly correlated with the target variable and have low intercorrelation, using a heuristic search to maximize relevance and minimize redundancy.
- **OneR:** Creates simple classification rules based on a single feature, selecting the one with the lowest error rate.

7.4 Simulated annealing

Simulated annealing is a metaheuristic technique inspired by the process of metal cooling, used to find optimal solutions in complex search spaces. In the context of feature selection, this method enables the exploration of different combinations of variables to identify subsets that optimize the performance of the predictive model.

The implementation of Simulated annealing in the caret package in R, through the safs function, efficiently performs the search for the optimal combination of features. The algorithm evaluates the model's performance at each iteration and accepts suboptimal solutions with a decreasing probability, which helps avoid local optima and improves the quality of the final solution.

8. Results

For the clustering analysis, the *k*-means and PAM algorithms were implemented, selecting a consistent configuration to ensure reproducibility and stability of the results. Both techniques were executed using a fixed seed value of 3, allowing for deterministic initialization of centroids and medoids, respectively. Moreover, 1000 iterations were configured to ensure convergence in each run, and 10 restarts (nstart = 10) were applied to evaluate multiple initializations and select the best partition based on the lowest intra-cluster distance.

Table 4 shows the silhouette analysis results obtained through the *k*-means and PAM algorithms, using the 42 selected variables from the dataset.

Table 4. Silhouette scores for different values of *k* using *k*-means and PAM

Algorithm	K Measures			
	K = 2	K = 3	K = 4	K = 5
k-means	0.53	0.47	0.46	0.40
PAM	0.50	0.48	0.43	0.38

Table 5 presents the results of the feature selection process using the CFS (Correlation-based Feature Selection) method from the FSelector library. This technique evaluates the relevance of variables, based on their correlation with the target variable and low redundancy with other selected variables. As a result, five optimal variables were identified and used to calculate the silhouette scores under different values of *k*. The evaluation was conducted incrementally, star- ting with the first two selected variables and progressively adding one variable at a time, evaluating the model's performance at each step. This approach allows us to observe how the quality of the clusters varies as new dimensions are introduced into the analysis.

Regarding table 6, it presents the results of the variable selectors generated by FSelector algorithms. These algorithms were executed incrementally, starting with the first two selected variables and progressively adding one more at each iteration until all features identified by each method were considered. However, only the best results for each algorithm are shown. Additionally, the variables that significantly contributed to achieving those values are specified, helping to identify the most representative subsets for each evaluated model.

Within table 7, there is a list of variables selected during the iterations that achieved the best silhouette results. As shown, three of the selectors initially identified the same two variables; however, as the iterations progressed, the selected variables diverged, revealing different selection behavior in subsequent stages.

Table 8 shows the results obtained using the Simulated annealing algorithm. At the end of the process, the model identified three optimal variables: `Nateglinide`, `Tolbutamide`, and `A1Cresult`. These variables represented the best performance when evaluated with the silhouette coefficient.

Table 5. Cluster analysis results for different subsets and *k* values

Subset	K	Silhouette Mean
gender, metformin	2	0.7189350
gender, metformin	3	0.8133443
gender, metformin	4	0.8938578
gender, metformin	5	0.9846291
gender, metformin, glyburide	2	0.6175232
gender, metformin, glyburide	3	0.7064362
gender, metformin, glyburide	4	0.6856388
gender, metformin, glyburide	5	0.7778758
gender, metformin, glyburide, change	2	0.4085565
gender, metformin, glyburide, change	3	0.4832919
gender, metformin, glyburide, change	4	0.5104543
gender, metformin, glyburide, change	5	0.5557880
gender, metformin, glyburide, change, cluster	2	0.3766780
gender, metformin, glyburide, change, cluster	3	0.3390272
gender, metformin, glyburide, change, cluster	4	0.3728791
gender, metformin, glyburide, change, cluster	5	0.3716568

9. Discussion

The results obtained confirm that the use of clustering algorithms effectively segments dia- betic patients into clinically relevant groups. Compared to previous studies, the silhouette va- lues obtained (up to 0.99 with Simulated annealing) exceed those reported by Zeng et al. (2021), who achieved maximum values of 0.78 using only *k*-means (5). This improvement occurs due to the use of Simulated annealing, which reduces dependence on initial conditions and optimizes the global search for centroids.

Table 6. Silhouette scores with different *k* values using FSelector algorithms

FSelector	K Measures			
	K = 2	K = 3	K = 4	K = 5
Chi-square	0.74	0.72	0.73	0.74
Information Gain	0.82	0.69	0.68	0.68
OneR	0.82	0.69	0.68	0.68
Random Forest	0.82	0.69	0.68	0.68
Relief	0.60	0.65	0.69	0.70

Table 7. Algorithms and selected variables

Algorithm	Selected variables
Chi-square	number_inpatient, number_emergency
Information Gain	number_inpatient, discharge_disposition_id
OneR	number_inpatient, discharge_disposition_id
Random Forest	number_inpatient, discharge_disposition_id
Relief	glimepiride, glipizide

Table 8. Silhouette scores for different *k* values using Simulated annealing

Algorithm	K Measures			
	K = 2	K = 3	K = 4	K = 5
Simulated annealing	0.72	0.82	0.98	0.99

Likewise, the results suggest that variables such as `A1Cresult`, `Nateglinide`, and `Tolbu- tamide` are key determinants for characterizing risk profiles, consistent with the findings of Li and Zhang (2023) regarding the importance of glycemic control and the use of medications in predicting readmissions (7). These patterns support the hypothesis that combining unsupervised methods with metaheuristics constitutes an effective alternative for exploratory analysis of complex clinical data.

10. Conclusion

The results obtained demonstrate that Simulated annealing is the most effective approach for identifying the global optimum in the analyzed dataset, compared to the other evaluated algorithms such as FSelector, *k*-means, and PAM. Through its ability to explore the solution space in a random-controlled manner, this algorithm avoids becoming trapped in local optima, allowing it to reach a solution closer to the optimal value. Performance evaluation showed that, compared to other methods, Simulated Annealing exhibited greater consistency in selecting the most representative variables and optimizing the established criteria.

The analysis of results reveals that different feature selection algorithms identified certain variables as highly relevant. For example:

- Chi-square selected: `number_inpatient` and `number_emergency`.
- Information Gain, OneR, and Random Forest all selected: `number_inpatient` and `discharge_disposition_id`.

- Relief identified: `glimepiride` and `glipizide`.
- Simulated annealing selected: `Nateglinide`, `Tolbutamide`, and `A1Cresult`.

This overlap between algorithms in selecting `number_inpatient`, `ischarge_disposition_id` highlights their importance as highly relevant variables that influence hospital readmission. Furthermore, the number of variables selected by each method ranged from 2 to 5, depending on the selection criteria and mechanisms of each algorithm.

Finally, these findings reinforce the value of unsupervised models in clinical data exploration. From a social and economic perspective, they can be used for more efficient and patient- centered decision-making.

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https://revistas.udistrital.edu.co/ojs/index.php/Tecnura/issue/view/1277

DOI: https://doi.org/10.14483/22487638.21867

REVISIÓN

Electrocoagulation as an Emerging Technology for Wastewater Treatment in Different Industries: A Review

Electrocoagulación como tecnología emergente al tratamiento de las aguas residuales en distintas industrias: una revision

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Fecha de Recepción: 17 de febrero de 2024 **Fecha de Aceptación:** 14 de noviembre de 2025

Cómo citar: Salcedo Díaz., A.L., Salcedo Mendoza., J.G., Hernández Ruydiaz., J.E., Figueroa Flórez., J.A. and Cervera Ricardo., M.A. (2025). Electrocoagulation as an Emerging Technology for Wastewater Treatment in Different Industries: A Review. *Tecnura*, 29(86), 75–99. https://doi.org/10.14483/22487638.21867

Abstract

The electrocoagulation (EC) technique has been considered a popular treatment alternative for the effective separation of organic and inorganic contaminants. This technique generates coagulating particles *in situ* through the electrolysis of a sacrificial anode that destabilizes suspended, dissolved, or emulsified contaminants in a liquid medium by inducing an electric field. EC has been widely studied due to its versatility, ease of installation, lower cost, and for being an environmentally friendly technology. For this article, a search and information-gathering phase was conducted in which Scopus, ScienceDirect, and Google Scholar were identified as the necessary tools for locating information on the electrocoagulation process as a wastewater treatment in various industries. This paper reviews studies on advances in EC applied to different types of industrial wastewater, focusing on evaluating the operating variables and optimal treatment conditions that are vital to the process. Likewise, the effect of the electrocoagulation on the quality properties of wastewater from different sectors is examined, considering factors such as current density, pH, reactor geometry, treatment time, and electrode spacing.

Objective: To determine the effect of the electrocoagulation process on the quality properties of wastewater from various industries as a function of physicochemical and geometric parameters.

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Methodology: A search and information-gathering phase was carried out using Scopus, Sciencedirect, and Google Scholar as the main sources. Subsequently, a scientific monitoring study was conducted following a methodology structured in four stages: planning, research, analysis, and competitive intelligence. Additionally, a literature review was conducted to identify needs and select keywords focused on the electrocoagulation process as a wastewater treatment technology in various industries.

Results: The review revealed that wastewater treatment removal efficiency is achieved by removing one or more of its components in whole or in part, depending on the initial or inlet organic load. The main parameters evaluated were Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), color, turbidity, Total Organic Carbon (TOC), and oil and grease content. Several studies have concluded that, under optimal treatment conditions, electrocoagulation can achieve approximately 90% removal of the pollutant loads in wastewater from diverse industrial sectors.

Conclusions: The review showed that electrocoagulation technology is a highly effective alternative for treating a wide variety of industrial effluents containing pollutants that cannot be effectively removed by conventional treatment methods. In addition, more research is needed to study the impact of new organic coagulant-assisted processes, reactor designs, electrode configuration, electrocoagulation mechanisms, processing conditions and electrode dissolution phenomena, in order to obtain greater removal and improvement in the treatment process.

Financing: The project was financed through the National Fund for Science, Technology, and Innovation of the General System of Royalties (Bank of National Investment Programs and Projects), the University of Sucre and the PADES group, within the framework of the project "Technological strengthening of the Colombian Caribbean region through the development of transformation processes of starchy raw materials (cassava, yams and sweet potatoes) in the department of Sucre", identified with the BPIN code 2020000100035.

***Keywords*:** Wastewater, electrocoagulation, quality properties, operating parameters, optimal conditions, electrocoagulation systems.

Resumen

La técnica de electrocoagulación (EC) se ha considerado una alternativa popular de tratamiento para la separación eficaz de contaminantes orgánicos e inorgánicos. Está técnica genera partículas coagulantes in situ mediante la electrolisis de un ánodo de sacrificio que desestabiliza los contaminantes suspendidos, disueltos o emulsionados en un medio líquido mediante la inducción de un campo eléctrico. La EC ha sido estudiada ampliamente debido a su versatilidad, facilidad de instalación, menor costo y por ser una tecnología amigable con el medio ambiente. Para la elaboración de este documento se realizó una fase de búsqueda y captación de información, en la cual se identificaron las herramientas de Scopus, Sciencedirect y Google Scholar como las herramientas necesarias para la búsqueda de información sobre el proceso de electrocoagulación como tecnología de tratamiento de aguas residuales en diversas industrias. En este documento, se han revisado estudios sobre los avances de la EC en varios tipos de aguas residuales en distintas industrias donde se han evaluado las variables operativas y condiciones óptimas de tratamiento que son vitales para el proceso de electrocoagulación. Asimismo, se establece el efecto del proceso de electrocoagulación sobre las propiedades de calidad de aguas residuales de las diferentes industrias, teniendo en cuenta los diversos parámetros que afectan al sistema, como densidad de corriente, el pH, la geometría del reactor, el tiempo de tratamiento y distancia entre los electrodos.

Objetivo: conocer el efecto del proceso de electrocoagulación sobre las propiedades de calidad de aguas residuales provenientes de diversas industrias en función de parámetros fisicoquímicos y geométricos.

Métodología: se realizó una fase de búsqueda y captación de información, en la cual se identificaron las bases de dato Scopus, Sciencedirect y Google Scholar como las principales fuentes para la búsqueda de información. Posteriormente, se realizó una revisión bibliográfica para identificar necesidades y seleccionar palabras claves enfocadas al proceso de electrocoagulación como tecnología de tratamiento de aguas residuales en diversas industrias.

Resultados: durante la revisión, se encontró que la eficiencia de eliminación del tratamiento de aguas residuales se logra eliminando uno o más de sus componentes en su totalidad o en parte, en función de la carga orgánica inicial o, de entrada. Los principales parámetros evaluados fueron Demanda Química de Oxígeno (DQO), Demanda Bioquímica de Oxígeno (DBO), sólidos suspendidos totales (SST), color, turbidez, carbono orgánico total (COT), contenido de aceite y grasa. Lo que llevó a que varios estudios concluyeran que en condiciones óptimas de tratamiento se logra una remoción efectiva de aproximadamente el 90% de la carga contaminante de las aguas residuales en diversas industrias.

Conclusiones: la revisión demostró que la tecnología de electrocoagulación ha sido una gran alternativa aplicada con éxito para el tratamiento de una amplia variedad de efluentes industriales que contienen contaminantes, los cuales no pueden ser eliminados de manera efectiva mediante métodos de tratamiento convencionales. Se evidenció también la necesidad de abarcar más investigaciones para estudiar el impacto de los nuevos procesos asistidos con coagulantes orgánicos, diseños de reactores, configuración de los electrodos, los mecanismos de electrocoagulación, las condiciones de procesamiento y los fenómenos de disolución de los electrodos, con el propósito de obtener una mayor eliminación y mejora en el proceso de tratamiento.

Financiamiento: el proyecto fue financiado a través del Fondo Nacional de Ciencia, Tecnología e Innovación del Sistema General de Regalías (Banco de Programas y Proyectos de Inversión Nacional), la Universidad de Sucre y el grupo PADES en el marco del proyecto "Fortalecimiento tecnológico de la región Caribe colombiana a través del desarrollo de procesos de transformación de materias primas amiláceas (yuca, ñame y batata) en el departamento de Sucre", identificado con el código BPIN 2020000100035.

***Palabras clave*:** Aguas residuales, electrocoagulación, propiedades de calidad, parámetros operativos, condiciones óptimas, sistemas de electrocoagulación.

Introducción

Electrocoagulation (EC) is defined as a process that destabilizes suspended and dissolved substances in a liquid medium by inducing an electric field in the effluent. This technology has been widely applied for the treatment of wastewater containing high loads of organic and inorganic pollutants, generating coagulants and hydroxides that destabilize suspended particles or absorb dissolved contaminants [1]. The technique mainly involves applying of an electric current to gradually dissolve a sacrificial anode during the reaction, thus producing a large number of highly charged metal cations *in situ*. These cations act as coagulants and are hydrolyzed near the anode to form M(OH)n hydroxides, while water is reduced to H_2 at the cathode. The resulting hydrogen bubbles promote floc formation, enabling contaminants to be removed through both precipitation and flotation [2].

The electrocoagulation process offers several advantages, including simple, easy-to-operate equipment, reduced sludge production, and the absence of added chemical reagents, which minimizes the risk of secondary pollution. The gas bubbles generated during electrolysis carry contaminants to the surface, facilitating their separation and collection. In addition, EC systems require minimal maintenance due to the controlled electrical potential and absence of moving parts, and they can be powered by renewable energy sources such as solar or wind [1]. Over recent decades, EC has been extensively studied as an effective technology for the treatment of various types of wastewater, enabling the removal of non-metallic inorganic species, heavy metals, organic pollutants, oils, greases, and real industrial effluents [3].

Electrocoagulation can be operated in either batch or continuous systems, depending on the type and concentration of contaminants. According to [4], the selection of reactor configuration depends on factors such as pollutant properties, effluent volume, application type, treatment time, current density, and operating conditions. Batch reactors are more suitable for laboratory and pilot-scale studies due to their smaller working volume, whereas continuous systems are preferred for large-scale industrial applications [21]. An EC reactor typically consists of an electrolytic cell equipped with sacrificial metal electrodes, commonly iron (Fe) or aluminum (Al), connected to a power source. The anodes and cathodes may be of the same or different materials [6]. Fe and Al plates are most commonly used because they are inexpensive, readily available, and highly efficient for pollutant removal [7].

In the food sector, particularly in the sugar industry, batch-type EC systems incorporating Fe, Al, and Cu electrodes have achieved removal efficiencies of up to 97% Similarly, studies in the dairy and meat industries using Fe electrodes in batch systems have reported pollutant removal rates above 90% [8]. In the textile industry, [9] implemented discontinuous EC systems with Al and Fe electrodes, achieving contaminant removal efficiencies above 80%. Likewise, [10] used stainless-steel electrodes in similar batch systems, reaching efficiencies of approximately 81%. Furthermore, [7] evaluated batch EC systems in the oil refinery industry using Al electrodes and obtained removal efficiencies close to 90%, while [11] reported comparable results using stainless-steel and Al electrodes. Altogether, these studies confirm that EC performance is strongly influenced by several parameters, including electrode material and configuration, applied current, treatment time, inter-electrode distance, current density, pH, and temperature [12].

Recent efforts have focused on optimizing EC reactor design to enhance pollutant removal rates and energy efficiency [13]. One of the main areas of technological development involves improving control over operational and influential variables, which determine the overall dynamics of the EC process [14]. [15] compared two EC reactor configurations for arsenic removal from groundwater in terms of efficiency and operating costs. The first reactor was air-fed and consisted of a round-bottomed base unit (150 mm in diameter, 45 mm thick) with several 2 mm holes, and a cylindrical titanium cathode perforated with 5 mm holes at 10 mm intervals. The second system was a batch reactor with vertically placed Fe plate electrodes (50–73 mm), where two anodes and two cathodes were connected in monopolar-parallel mode. The first configuration achieved 99.3% arsenic removal at an operating cost of $\$1.55/m^3$, while the second achieved 96.9% removal at only $\$0.10/m^3$.

To date, most research has explored hybrid EC systems that integrate other advanced technologies to enhance pollutant removal capacity and treatment performance [16]. Other studies, such as [17], have focused on electrode reactions and pollutant removal mechanisms, including kinetic models, adsorption isotherms, and efficiency analysis. Similarly, [7] investigated EC performance across different wastewater types, in order to evaluate operational variables and comparing EC with conventional chemical coagulation, since these parameters largely govern removal mechanisms. Nonetheless, significant knowledge gaps remain regarding the effects of electrocoagulation on the physicochemical quality of wastewater from agro-industrial processes. Therefore, this review aims to assess the impact of the electrocoagulation process on the quality parameters of wastewater from various industries, as influenced by physicochemical and geometrical operating conditions.

Principles of electrocoagulation

Electrocoagulation is a process that removes pollutant loads from wastewater by applying an electric current using electrodes (anode and cathode), which can be made of the same or different materials (Al–Al, Fe–Fe, Al–Fe, Fe–Al). During electrolysis, the anode material undergoes oxidation, generating metallic ions such as Al^{3+} or Fe^{2+}/Fe^{3+}, depending on the electrode used. These cations act as *in situ* coagulants, promoting the formation of aluminum and iron hydroxides ($Al(OH)_3$, $Fe(OH)_2$, $Fe(OH)_3$) which facilitate the aggregation and removal of pollutants [18], [19]. Simultaneously, the hydrogen gas produced at the cathode aids in contaminant flotation, bringing them to the surface as floating sludge [6], [20].

Electrodes in EC systems may be arranged in either monopolar (MP) or bipolar (BP) configurations [21]. The MP configuration can consist of electrodes connected in parallel (MP-P) or in series (MP-S) arrangements [21]. In the MP–P configuration (Fig. 1A), under direct current (DC) conditions, the electrodes are alternately connected so that the current flow is evenly distributed across the entire electrode array [19]. Conversely, in the MP–S configuration (Fig. 1B), only the two external electrodes (anode and cathode) are connected to the power supply, with no interconnection to the internal electrode pairs [18]. These internal electrodes, often referred to as sacrificial electrodes, help reduce anode dissolution and cathode passivation [13].

In the BP configuration (Fig. 1C), the external electrodes are connected to the power supply, whereas the internal (sacrificial) electrodes remain electrically unconnected [19]. As a result, the array contains both bipolar (internal) and monopolar (external) electrodes, and the system operates in a series connection mode [18]. By contrast, in bipolar parallel (BP–P) configurations, the sacrificial electrodes are alternated between two parallel plates that are not directly connected to the power source [5].

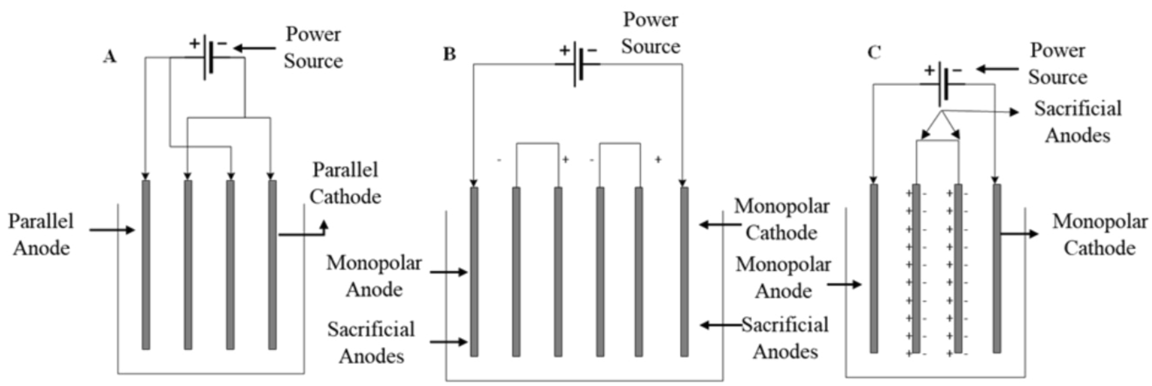

Figure 1. *EC reactor with different electrode arrangements at discontinuous scale: (A) Monopolar parallel connection (MP-P); (B) Monopolar series connection (MP-S); (C) Bipolar series connection (BP-S).*

Note. **Source:** Adapted from [18].

Electrocoagulation systems

The systems used in the electrocoagulation process play a crucial role in determining the removal efficiency of organic and inorganic loads present in industrial effluents. Several factors must be considered, including cell design, reactor type, electrode configuration, electrode material, plate thickness, and the distance between electrodes [22]. It should be emphasized that the electrode configuration is one of the most critical parameters for achieving higher removal efficiencies in EC systems [23]. The electrocoagulation process generally occurs in several stages: (I) generation of metal cations in the system; (II) formation of hydroxyl ions through the cathodic hydrolysis process; (III) interaction between metal cations and hydroxyl ions to form metal hydroxides; (IV) oxidation of toxic contaminants in to less toxic species; (V) neutralization of contaminants by metal hydroxides; (VI) contaminant removal by sweep coagulation; and (VII) flotation of the formed flocs to the surface assisted by hydrogen gas generated at the cathode [6].

In EC, contaminant removal primarily occurs through adsorption, coagulation, and flotation mechanisms [7]. During anodic dissolution, coagulant species (metal ions) are produced *in situ* (Equation 1), accompanied by the generation of hydroxyl ions (Equation 3) and hydrogen gas at the cathode (Equation 2). These coagulants facilitate the formation of flocs composed of metal hydroxides, which act as effective adsorbents for contaminant removal [20]. Furthermore, the hydrogen gas produced at the cathode aids in lifting these flocs to the water surface, forming a layer of floating sludge [24].

At the anode:

$$M_{(s)} \rightarrow M^{n+}_{(aq)} + ne^- \tag{1}$$

$$H_2O \rightarrow 4H^+_{(aq)} + O_{2(g)} + 4e^- \tag{2}$$

At the cathode:

$$nH_2O + ne^- \rightarrow (^n/_2)\ H_{2(g)} + nOH^-_{(aq)} \tag{3}$$

Reactions for Al electrodes

When aluminum (Al) is used as the electrode material, cationic monomeric species such as Al^{3+} and $Al(OH)^{2+}$ (Equation 4) are generated at low pH. At optimal pH conditions, these species are transformed into $Al(OH)_3$ (Equation 5), which can subsequently polymerize to form $Al_n(OH)_{3n}$ (Equation 6) [18].

$$All_{(s)} \rightarrow Al^{\ 3}_{(\ aq}{}^{+)} + 3_e^{\ -} \tag{4}$$

$$Al3^+_{(aq)} + 3H_2O_{(l)} \rightarrow Al(OH)_{3(s)} + 3H^+_{(\ aq)} \tag{5}$$

$$nAl(OH)_3 \rightarrow Aln(OH)_{3n} \tag{6}$$

Reactions for Fe electrodes

When iron (Fe) is used as the electrode material, oxidation reactions at the anode lead to the formation of iron hydroxides, $Fe(OH)_n$ (n = 2 or 3). Two main reaction systems are recognized: the first leading to $Fe(OH)_3$ formation and the second to $Fe(OH)_2$ [18].

System 1:

Anode:

$$4Fe_{(S)} \rightarrow 4Fe^{\ 2}_{(\ aq}{}^{+)} + 8e^- \tag{7}$$

$$4Fe^{\ 2}_{(\ aq}{}^{+)} + 10H_2O_{(l)} + O_{2(g)} \rightarrow 4Fe(OH)_{3(S)} + 8H^+_{(\ aq)} \tag{8}$$

Cathode:

$$8H^+_{(\ aq)} + 8e^- \rightarrow 4H_{2(g)} \tag{9}$$

General:

$$4Fe_{(s)} + 10H_2O_{(l)} + O_{2(g)} \rightarrow 4Fe(OH)_{3(s)} + 4H_{2(g)} \tag{10}$$

System 2:

Anode:

$$Fe_{(s)} \rightarrow Fe^{\ 2}_{(\ aq}{}^{+)} + 2_e^{\ -} \tag{11}$$

$$Fe^{\ 2}_{(\ aq}{}^{+)} + 2OH^-_{(\ aq)} \rightarrow Fe(OH)_{2(S)} \tag{12}$$

Cathode:

$$2H_2O_{(l)} + 2_e^{-} \rightarrow H_{2(g)} + 2OH^{-}_{(aq)} \tag{13}$$

General:

$$Fe_{(s)} + 2H_2O_{(l)} \rightarrow Fe(OH)_{2(s)} + H_{2(g)} \tag{14}$$

It is important to note that several operating parameters significantly influence the efficiency of the electrocoagulation process: (1) initial pH: affects current efficiency and the rate of metal dissolution to form hydroxides. It also varies during electrolysis depending on electrode material and initial water chemistry; (2) electrocoagulation time: determines the extent of anodic dissolution and coagulant release; therefore, treatment efficiency depends on the concentration of metal ions produced; (3) distance between electrodes: as the distance increases, resistance between electrodes rises, reducing ion transport and hydroxide formation; (4) current density: higher current densities increase ion generation but can also cause excessive heating, reducing treatment efficiency; (5) type and concentration of the electrolyte: higher electrolyte concentrations increase conductivity and decrease resistance, directly enhancing removal efficiency. Conductivity itself depends on the total concentration of dissolved solids [1], [25], [26].

Use of the electrocoagulation process in different industries.

Wastewater generated by the food industry is characterized by high concentrations of Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), as well as elevated levels of fats, oils, and grease. According to [8], a batch-type electrocoagulation system was employed, consisting of a rectangular acrylic reactor with an approximate capacity of 12 L (Fig. 2A). Depending on the experimental design, the variables considered were the number of electrodes and treatment time, with electrode configurations of 3, 6, and 13 units. Iron and aluminum were used as electrode materials, arranged side by side with an interelectrode distance of 20 mm. At the same time, the electrodes were connected to a direct current (DC) power source with a voltage range of 0–60 V and a maximum output of 30 A (Fig. 2A). A working voltage of 12 V was selected to protect the power supply and prevent accidents during operation, since higher currents could exceed the limits permitted by the equipment (Fig. 2B). The results demonstrated an effective pollutant removal performance, achieving rates above 95 %.

Regarding the types of systems used by these authors [8], it can be stated that batch electrocoagulation reactors, when operated under optimal conditions, significantly improve water quality due to their efficiency in removing organic loads and pollutants. Their main advantage lies in their operational flexibility, making them particularly suitable for industries that handle variable production processes. This adaptability allows implementation without requiring new facilities or substantial structural modifications [8].

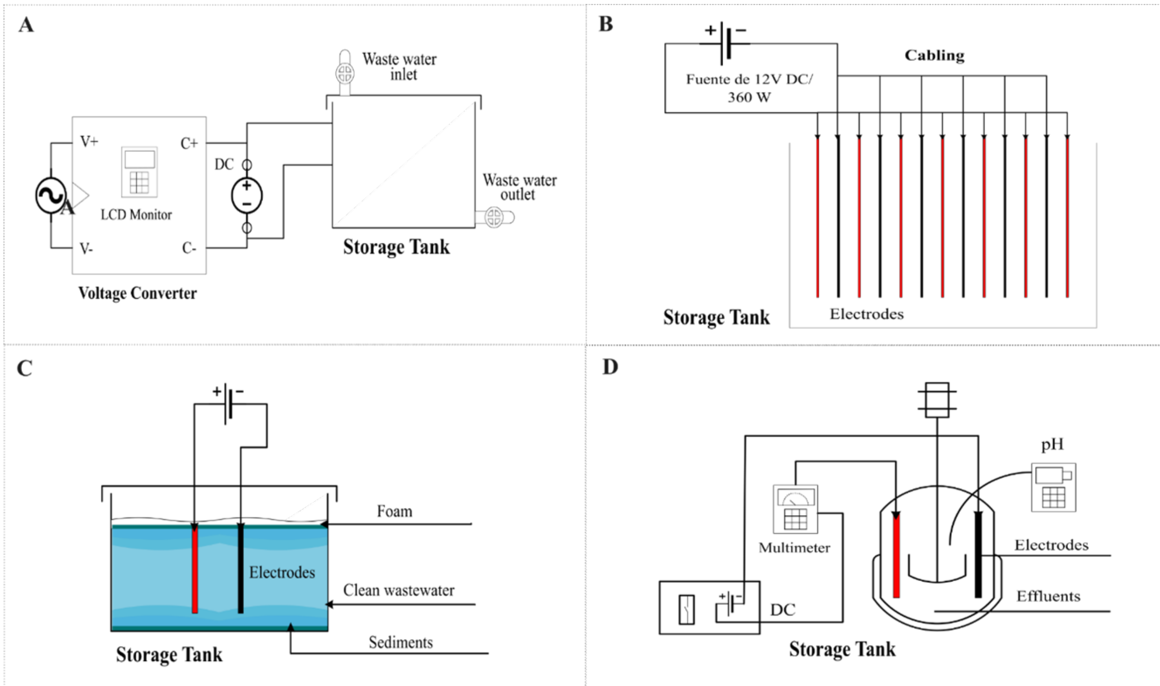

Figure 2. *Electrocoagulation systems used in different industries: (A) Batch-type electrocoagulator assembly with monopolar electrodes connected in parallel; (B) Connection configuration of the iron electrodes; (C) Treatment of rubber waste by the electrocoagulation method; (D) Schematic diagram of the assembly.*

Note. **Source:** Adopted from [8], [11], [27].

In the rubber industry, [27] employed a batch-type electrocoagulation system equipped with aluminum and stainless-steel electrodes, regulator units, digital multimeters, and anode–cathode connection cables. The experimental setup allowed the variation of both processing time and electrode material. The electrodes measured 11 cm × 11 cm, with a spacing of 1 cm between them. Voltage varied between 12 and 18 V, with treatment durations of 30, 60, 90, 120, and 150 minutes. Under these conditions, pollutant removal efficiencies of approximately 85 % were achieved. The waste treatment equipment used in this study is shown in Fig. 2C.

In the textile industry, [10] set a cylindrical electrolytic reactor made of acrylic, with dimensions of 60.0 cm in height and 10.0 cm in diameter (Fig. 2D). Stainless-steel plate electrodes were connected in a bipolar series configuration. Power consumption was monitored using a wattmeter and a voltage source of 13.8 V. 20 A was applied through an electrical circuit capable of generating current pulses between 0 and 2,200 Hz. This system achieved pollutant removal efficiencies that exceeded 85 %.

Reference [28] employed a plate-electrode reactor to treat laundry industry wastewater (LWW). Optimization of the treatment considered parameters such as electrolysis time, pH, and current density, with experiments performed in batch mode (Fig. 3A). The reactor contained seven electrodes (four anodes and three cathodes), with an effective anodic surface area of 350 cm² per side and an interelectrode distance of 10 mm. Under these conditions, an organic load removal efficiency of approximately 87 % was obtained.

Similarly, in oil refinery industries, [29] applied an electrocoagulation system based on a monopolar cylindrical batch reactor made of Pyrex glass, measuring 25 cm in height and 14 cm in diameter. The cathode was made of stainless steel and the anode of aluminum, each measuring 15.0 cm × 7.2 cm × 3 mm thick. Direct current was supplied by a DC power source operating between 0 and 30 V with a maximum of 5 A. The experimental setup also included a magnetic stirrer to ensure proper mixing. The treatment achieved removal efficiencies close to 90 %. A schematic representation of the reactor configuration is shown in Fig. 3B.

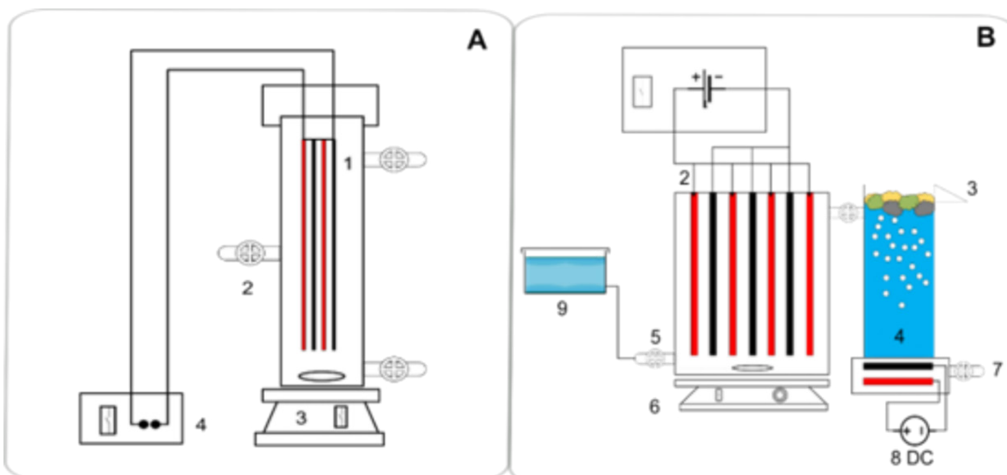

Figure 3. *A) Experimental scheme of the electrocoagulation system: 1: Set of electrodes; 2: collection tap; 3: magnetic stirrer; 4: electrical voltage source. B) Combined electrocoagulation (EC) and electroflotation (EF) treatment system at laboratory scale: 1-DC power for the EC cell; 2-Cell EC; 3-Floating link; 4-FE cell; 5-AR inlet; 6-Magnetic-stirring bar; 7- Purified Ar output; 8- DC for EF cell; 9-Feed sludge tank.*

Note. **Source:** Adopted from [10], [28]

This review highlights that, for wastewater treatment in oil refinery industries, the electrocoagulation technique offers distinct advantages over traditional chemical coagulation methods. These include lower sludge production, reduced chemical consumption, and consequently, lower operational costs. Moreover, optimization of parameters such as cell voltage and solution pH can lead to notable reductions in energy consumption while enhancing pollutant removal efficiency. The use of specially engineered aluminum alloys and the periodic alternation of anode and cathode roles have also been reported to delay electrode passivation, thereby improving system durability and performance [10].

METHODOLOGY

The search for information in the scientific surveillance study was established using the methodology proposed by [30], which is structured into four (4) stages: planning, research, analysis, and competitive intelligence: the different stages of the surveillance study are described below:

Planning: The planning stage began with the definition of the main topic being "Implementation of emerging technologies in the treatment of industrial wastewater" being delimited by "Electrocoagulation". First, a log was created based on a previous bibliographic review to establish key words related to the subject. Having this, it was necessary to validate the words found in order to obtain the search matrix, which was composed of three keywords or expressions combined with three Boolean operators AND, OR, and AND NOT.

Search: After developing the search matrix, information was retrieved from the digital platform Scopus and PatentInspitation, allowing to verify and analyze the results, offering an overview of the scientific and technological production across different areas of science. The search was limited to the period from 2016 to 2022.

Information analysis: the Scopus tool made it possible to identify trends and establish correlations with the subject matter or the general search matrix. Likewise, the VOSviewer tool was used to identify correlations and research prospects, refining the information obtained from Scopus and retaining only the keywords most closely related to the topic. Once this is done, several clusters associated directly and indirectly with the search are created.

Competitive intelligence: Finally, a validation of the data obtained was carried out, through which trends were identified in different areas such as the use of the electrocoagulation process and the potential validation of these emerging technologies at the industrial level. In addition, it was possible to identify future projections in the use of assisted systems as advanced processes for wastewater treatment in various industries.

RESULTS AND DISCUSSION

Effect of electrocoagulation systems on the quality of liquid effluents produced in different industries.

Removal efficiency: The removal efficiency in wastewater treatment is defined in relation to the initial pollutant load and it is typically expressed based on the total or partial separation of one or more of its components. Among the typical parameters evaluated are COD, BOD, TSS, color, turbidity, TOC, and oil and grease content. In their study on wastewater in the rubber industry, the authors of [27] reported that the implementation of an electrocoagulation system using aluminum and stainless-steel electrodes effectively reduced pollutants in wastewater samples. This was evidenced by reductions in TSS, COD, BOD, and NH_3 under conditions of 18 V and 150 min (Table 1). Likewise, [8] demonstrated in the food industry that optimal EC conditions for contaminant removal from dairy and meat wastewater involved the use of 13 iron electrodes, a current density corresponding to 12 V, and a treatment time of 60 min, which achieved approximately 90% removal of total COD, soluble COD, and turbidity. Other authors working in the food sector obtained comparable results, with removal efficiencies exceeding 90%, employing mild steel electrodes arranged in a parallel configuration, spaced 2 cm apart, and a treatment time of 60 min [31]. However, [32] reported slightly lower removal efficiencies, around 85%, using aluminum electrodes with 6–12 plates, an electric potential between 6–12 V, and reaction times of 30–60 min.

In the textile industry, [9] applied aluminum and iron electrodes under conditions of pH 8, a treatment time of 80 min, a current density of 20 A/m^2, and an electrode spacing of 3 cm. Their results showed high efficiency in contaminant removal, measured through COD and color reduction, leading to significant improvement in wastewater quality. For their part, [10] obtained similar results, achieving nearly 85% removal efficiency by using stainless-steel electrodes under conditions of constant agitation at 200 rpm, a pulse frequency of 1.0 Hz, electrode spacing of 1 mm, and a reaction time of 50 min.

On the other hand, in the electroplating industry, several studies have shown that under conditions of pH 9 and a current density of 2 mA/cm^2, close to 90% heavy metal removals can be achieved. This efficiency strongly depends on the current density, as higher current levels enhance metal removal [33]. However, [29] in electrocoagulation studies for oil refineries obtained higher removal values than those obtained by Kim *et al.*, (2020), which were above 90 %. These results conducted under optimal conditions of pH 6, DC current of 35 mA/cm^2, a treatment time of 120 min, and the use of aluminum and stainless-steel electrodes. Such performance is likely influenced by factors such as electrode type, spacing, dimensions, and applied voltage. In a recent study on wastewater treatment from the cardboard industry, [34] it was shown that, under optimal conditions of pH 6.62, an electric current of 10 A and a KCl concentration of 0.5 mol/L, removal efficiencies greater than 90% were achieved for the contaminants.

Total suspended solids (TSS): Total suspended solids (TSS) refer to organic and inorganic substances retained by a filter and measured through gravimetric analysis. As a key indicator of water quality, TSS levels are critical for assessing the performance of wastewater treatment processes [35]. Electrocoagulation has demonstrated significant potential for TSS removal; however, its efficiency is highly dependent on the specific industrial application and operational parameters. For instance, in the rubber industry, a system utilizing aluminum and stainless steel electrodes operating at 18V for 150 minutes achieved an 85.39% reduction in TSS [27]. However, the study noted that TSS levels exhibited instability, likely due to electrode decomposition during treatment and differences in voltage measurement that may introduced quantification inaccuracies. In contrast, exceptional results have been achieved in the food industry. A comparative study between electrocoagulation and electro-Fenton processes reported TSS removal efficiencies exceeding 99% for both methods under their respective optimal conditions [36]. This high efficiency is attributed to a greater electrode dissolution rate, which promotes the formation of active coagulants. The authors further clarify that elevated TSS concentrations contribute directly to increased water turbidity, thereby raising the oxygen demand required for organic matter degradation.

In addition, the versatility of the technology is highlighted by its use in the electroplating sector. An electrocoagulation-flotation system employed as a primary treatment for petroleum refinery wastewater achieved a 90% TSS removal efficiency. This performance was measured under optimized conditions, including a current density of 11.3 mA/cm², an initial pH of 6.8, a temperature of 30 °C, a 30-minute treatment time, and a gas flow rate of 0.8 L/min (Table 1) [37].

Further advancements in the textile industry have explored electrocoagulation using pulsed direct current. With stainless steel electrodes, an agitation speed of 200 rpm, a pulse frequency of 1.0 Hz, a 1 mm electrode gap, and a 50-minute treatment time, a 50% TSS removal efficiency was observed [10]. This study underscores that electrode material has a direct impact on pollutant removal rates and recommends further investigation to establish its precise effect on final effluent quality.

Biochemical Oxygen Demand (BOD): The biochemical oxygen demand (BOD) is an analytical parameter that quantifies the amount of oxygen consumed by microorganisms to decompose organic matter in water, serving as a critical indicator of wastewater pollutant load [35]. Electrocoagulation has proven to be an effective technology for reducing BOD across various industries. In the rubber industry, for example, a system employing aluminum and stainless steel electrodes operating at 18 V for 150 minutes achieved a significant BOD reduction of approximately 57%, markedly improving wastewater quality (Table 1) [27]. As the authors explain, a high BOD level signifies a substantial concentration of organic pollutants, which elevates the oxygen demand for microbial decomposition. Even more pronounced results have been demonstrated in the soft drink industry. Using iron and aluminum electrodes with a 2-hour treatment time and the addition of 0.5% bittern a concentrated solution of chlorides, sulfates, and other minerals a remarkable BOD removal of nearly 95% was attained [38]. This high efficiency is likely attributable to the synergistic effect of the sufficient electrocoagulation time and the addition of bittern, which enhances ionic conductivity and promotes coagulation. Similarly, exceptional performance was observed in the fishing industry. The electrocoagulation-flotation process, configured with 8 aluminum electrodes, a 10 mm inter-electrode distance, a 5 A direct current, and a 15 V potential, yielded a 97.5% BOD removal efficiency [39]. The researchers attribute this success to the optimized current density and voltage potential, which intensify the electrochemical reactions necessary for the breakdown of organic pollutants.

Chemical Oxygen Demand (COD): The chemical oxygen demand (COD) is a critical parameter for assessing wastewater pollution, measuring the total quantity of oxygen required to chemically oxidize organic matter in a water sample [35]. The efficacy of electrocoagulation in reducing COD has been demonstrated across diverse industries, though with varying outcomes dependent on specific operational parameters. In the rubber processing industry, a system utilizing aluminum and stainless steel electrodes achieved a moderate COD reduction of 56.14% (Table 1) [27]. In contrast, significantly higher efficiencies have been reported in sectors with high organic loads. For the combined dairy and meat industry, researchers using a 13-electrode iron configuration at 12 V for 60 minutes reported maximum reductions of 96% for total COD and 95% for soluble COD (Table 1) [8]. The authors note that the elevated initial COD values are likely due to the complex matrix of suspended solids, dissolved substances, and significant organic load characteristic of these mixed operations.

Similarly, exceptional performance was observed in the sugar industry. Employing iron, aluminum, and copper electrodes at an optimal pH of 6, a current density of 156 A/m², and a remarkably short treatment time of 15 minutes, a COD reduction efficiency of 97.8% was achieved (Table 3) [40]. This high efficiency is attributed to the increased current density, which accelerates the formation of metal ions that destabilize and remove contaminant particles.

In turn, demonstrated the process's versatility, in the textile industry utilizing pulsed direct current with an agitation speed of 200 rpm, a pulse frequency of 1.0 Hz, and a 1 mm electrode spacing achieved 81.23% COD removal within 50 minutes (Table 1) [10]. This work highlights that electrode material is a critical factor directly influencing removal rates and recommends further study to optimize this variable.

Finally, consistent high performance has been documented in the challenging context of oil refinery wastewater. One study using a cylindrical reactor with aluminum and stainless steel electrodes at pH 6, a current density of 35 mA/cm², and a 120-minute treatment time achieved 90% COD removal [29]. The authors found that neutral pH and increased current density were key to this favorable outcome. Corroborating these findings, another study in the same industry reported a similar 90% COD reduction under conditions of 11.3 mA/cm² current density, pH 6.8, and a 30-minute coagulation time (Table 1) [37]. This research further concluded that the COD removal rate exceeded 90% and that the efficiency of the airlift electrocoagulation reactor is governed by both the applied current density and the fluid flow rate.

Nitrates: Nitrates, characterized by nitrogen in its highest oxidation state, are a naturally occurring ion within the nitrogen cycle. While chemically stable, they can be reduced through microbial denitrification [41]. In water analysis, nitrate concentration is typically quantified via ultraviolet spectrophotometry at 275 nm and serves as a key parameter for monitoring waters with low organic matter content [35]. The efficacy of electrocoagulation (EC) for nitrate removal appears to be industry-specific, with notable success in certain food processing sectors. A study on poultry and dairy slaughterhouse wastewater demonstrated that a sequential treatment combining anodic oxidation (EOR) with electrocoagulation achieved near-total nitrate removal (~99%) (Table 1) [31]. The optimized system, employing stainless steel electrodes across a broad pH range (2-12) and treatment times up to 360 minutes, leveraged the synergistic effect of both processes. This combined approach effectively addressed the complex mixture of pollutants, producing an effluent suitable for discharge or reuse. Beyond industrial wastewater, electrocoagulation has also been applied to remediate nitrate-contaminated groundwater. Research by [42], using aluminum electrodes at 30 V, a 1.8 cm electrode gap, and a 120-minute treatment time, reported consistent nitrate removal efficiencies between 88.48% and 94.1% across various water samples.

Prospective Electrocoagulation Processes in Agro-industries

Electrocoagulation technology has been shown to be a very viable alternative in the removal of organic and inorganic contaminants from various water sources (municipal water, wastewater, lake water, river water and seawater) [26]. Based on the various scientific studies carried out on the subject, a scientific surveillance study was planned, using different search tools such as ScienceDirect, Google Scholar and Scopus to filter documents with necessary and coherent information, with a time range from 2016 to 2022. Likewise, the use of VOSviewer made it possible to purify all the information obtained from Scopus and to establish intercorrelated thematic lines, taking into account a series of keywords and obtaining as a result the thematic map shown in Figure. 4, which consists of five (5) clusters related to the electrocoagulation process. The following is a description of each cluster obtained:

Red cluster: Integrated Wastewater Treatment Strategies

This cluster centers on broader wastewater treatment frameworks, highlighting terms such as electric field, biological treatment, bioremediation, and denitrification [43](Fig. 4). It acknowledges that while many treatment processes exist, they often face limitations in cost, efficiency, time, or the generation of secondary waste [18]. A significant research prospect emerging from this cluster is the development of hybrid systems that combine electrocoagulation with other technologies to enhance removal efficiencies across different effluent types.

Green cluster: Electrocoagulation Performance and Parameters

This group focuses directly on the electrocoagulation process as a versatile technology for wastewater treatment. It shows a strong emphasis on key performance indicators like turbidity, color, and chemical oxygen demand (COD) removal (Fig. 4). Critical operational factors such as the use of aluminum anodes and overall treatment efficiency are also prominent, as these are fundamental to process performance [23]. A notable gap is the relative limited attention given to other crucial parameters like biological oxygen demand (BOD), phosphates, total suspended solids (TSS), and total solids (TS). Future research should aim to include these parameters to provide a more comprehensive evaluation of treatment efficacy for specific agro-industrial effluents.

Purple cluster: Comparison with Chemical Coagulation

The prominent theme here is chemical coagulation, a conventional process where chemicals are added to remove impurities via agglomeration and precipitation [18]. A study in the pharmaceutical industry [44] compared this method with electrocoagulation, finding chemical coagulation with alum and FeCl3 removed only 14.05% and 26.3% of total dissolved solids (TDS), respectively. In contrast, electrocoagulation achieved superior removal of both COD (92.3%) and TDS (91.5%). This comparison highlights a significant research opportunity: the systematic evaluation of combined coagulation-flocculation and electrocoagulation processes for agro-industrial wastewater, where such hybrid approaches are still underexplored.

Yellow cluster: The Role of Natural Coagulants

This research line connects electrocoagulation with natural coagulants. Key terms include biochemical oxygen demand and water purification. For instance, *Tamarindus indica* seeds were used as a natural coagulant in the dairy industry, achieving 71% TDS and 75% COD removal [45]. Another study on pharmaceutical wastewater achieved a 78.23% COD reduction using a combination of natural and chemical coagulants with electrocoagulation [44]. A study compared combined treatment processes using coagulation-flocculation (CF) and electrocoagulation techniques in wastewater from the pharmaceutical industry (PIWW), using natural coagulants and chemical coagulants, achieving a COD reduction percentage of 78.23 %. The terms coagulation-flocculation refer to physicochemical processes that have the potential to reduce pollution and provide clean water for reuse in water and wastewater treatment (Fig. 4). Although this term is related to the electrocoagulation process, there are few studies in which these combined systems have been used, however, in agro-industrial processes there are scientific gaps in terms of wastewater treatment, which would be a good prospect for future research.

Blue cluster: Process Mechanisms and Hybrid Technologies

This cluster describes the fundamental phenomena of the electrocoagulation process, highlighting concepts such as electrode degradation, presence of anodes, cathodes, and electro-oxidation processes (Fig. 4). It is also related to alternative technologies such as activated carbon treatments, which is used as an absorbent due to its large surface area and high absorption rate of organic and inorganic contaminants [43]. In addition, advanced ultrasound-assisted oxidation processes for complex effluent treatment, as it has a remarkable impact on the efficiency and removal of pollutants. According to [46] showed in their research an average pollutant removal efficiency of more than 90 % for color, turbidity, BOD, oil and grease, using electrocoagulation-ultrasound-assisted flotation (ECF/US) processes and Al/Fe electrodes with a treatment time of 25 min.

It is important to highlight the need for future research studies to quantify reductions in electrode material consumption, sludge production, and energy use during the electrocoagulation process.

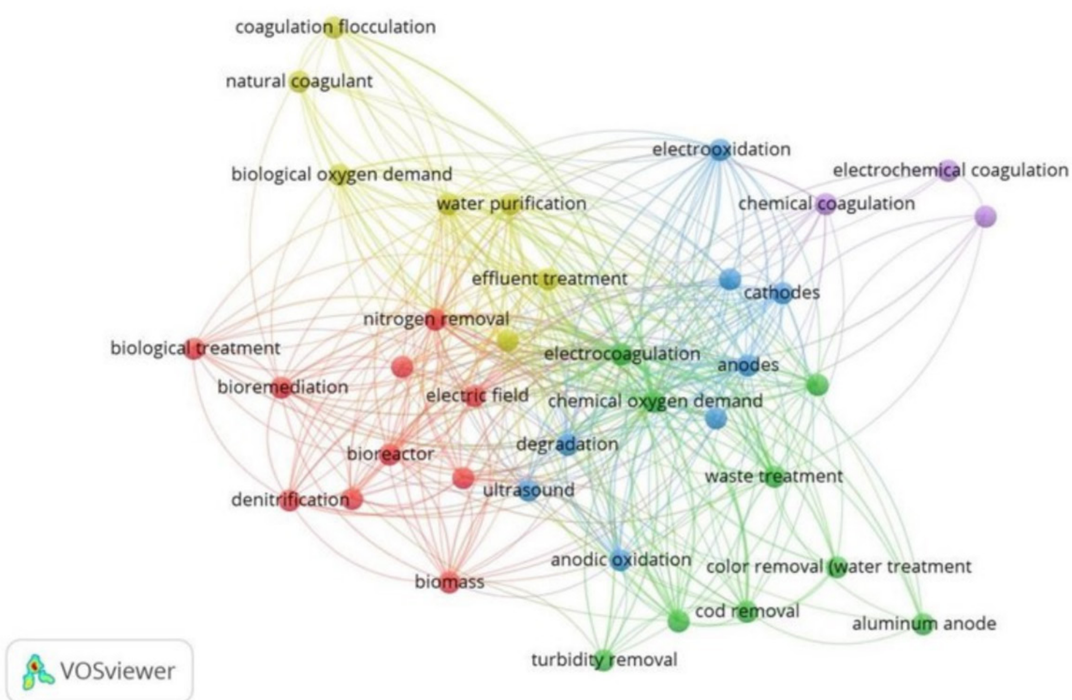

Figure 4. Cluster of scientific surveillance related to the electrocoagulation process.

Note. **Source:** Own elaboration

Although the electrocoagulation technique shows high potential for removing contaminants from various water sources, it still lacks large-scale implementation, as most of the published studies have been conducted on a laboratory scale, providing only a small amount of information. Therefore, further research is needed to study the impact of new reactor designs, electrode configuration, electrocoagulation mechanisms, processing conditions, and electrode dissolution phenomena. Additional analysis is also required to determine the operating conditions of the process at the agro-industrial level. Also, future studies should be conducted on the reduction of electrode consumption and process efficiency on water quality properties.

Table 1. *Application of the electrocoagulation process for the treatment of various industrial effluents.*

Industry	Electrodes	Optimal conditions	Removal efficiency (%)	Water quality properties	Reference
Rubber industry	Aluminum and stainless steel	Voltage of 18V and processing time of 150 min.	56.14	An effective reduction of TSS of 85.39 %; COD 56.14 %; BOD 57.18 % and NH3 73.5 % was achieved.	[27]
Cardboard industry.	Aluminum	pH of 6.62, electric current of 10A, electrode spacing of 3 mm, KCl at 0.5 mg/L.	54	The EC technique obtained a COD efficiency of 54 %, color and turbidity greater than 95 %.	[34]
Soft drink industry	Iron and Aluminum	The operating time at the levels was 2, 4 and 6 min.	98.31	A COD removal rate of 98.31 % and BOD removal rate of 95.00 % was achieved.	[38]
Sugar Industry	Mild steel	Treatment time was 100 min, pH 6.66 and DC of 104 A/m^2.	75.98	The EC had a COD removal rate of 75.98 %.	[47]
Potato processing industry	Aluminum	pH between 6 and 7.5, time of 20 min, DC greater than 1.6 and conductivity above 4.	70	The EC process achieved a COD removal of more than 70 %.	[48]
Domestic wastewater	Iron and Aluminum	pH between 7 and 8.2, current intensity of 7 A and time of 15 min.	80	Electrocoagulation achieved a COD removal greater than 80 %.	[49]
Food industry	Iron	Time 21 and 36 min, pH 10 and current density 86 mA/cm^2	59.1	The EC obtained a high COD removal of 59.1 % and TSS removal of more than 99 %.	[36]
Textile Industry	Stainless steel	stirring speed of 200 rpm, pulse frequency of 1.0 Hz, electrode distance of 1 mm and time of 50 min.	81.23	The EC process obtained a COD reduction of 81.23 %; color 98.94 %; turbidity 85.87 %; TSS 45.98 %; sulfate 98.75 % and sulfide 55.2 %.	[10]
Swine industry	Iron and Aluminum	DC of 2.94 mA/cm^2 and a reaction time of 60 min.	81	The EC allowed a reduction of COD up to 81 %; color of 82 % and ST of 91 %.	[50]
Sugar Industry	Iron, aluminum and copper.	pH 6, DC 156 A/m2, electrode distance 20 mm, treatment time 15 min.	97.8	The EC showed a COD reduction of 97.8% and a color removal of 99.7%.	[40]
Dairy and meat industry	Iron	13 electrodes, DC at 12 V, electrode spacing of 20 mm and a reactor operating time of 60 min.	96 & 95	The process achieved a total COD removal of 96 %, soluble COD of 95 % and turbidity of 94 %.	[8]
slaughterhouse industry	Aluminum and Iron	10 electrodes, electrode spacing of 1 cm, DC in the range of 4.54 to 18.18A/cm^2 and treatment time 60 min.	79	The EC assisted with anaerobic digestion obtained a removal of more than 79% of COD, 95% of nitrate and 90% of turbidity.	[24]
Lacto Whey Industry	Iron, Aluminum and Stainless Stee	Fe / AISI 304	* (COT) 49.1	The EC process produced a higher removal (TOC) of 49.1 %.	[51]

Continued Table 1.

Industry	Electrodes	Optimal conditions	Removal efficiency (%)	Water quality properties	Reference
Pig Slaughterhouse	Aluminum and Aluminum/ Iron	5 A DC, 6 V potential, 10 mm electrode spacing and 60 min time, with Al electrodes.	*Color 97; turbidity 97.4; BOD 93 & oil and grease 90.	The EC with Al electrodes, obtained removal of color 97 %; turbidity 97.4 %; BOD 93 %, oil and grease 90 %; Al/ Fe removal of color 95.5 %; turbidity 96.2 %; nitrogen 93.4 %; and BOD 90.7 %; oil and grease, was < 90 %.	[52]
Electroplating	Iron and Aluminum	pH 9, DC of 2 mA/cm^2	*Removal of heavy metals (Cu, Zn, Ni and Cr).	The EC process showed higher removal efficiency of heavy metals about 90 % (Cu, Zn, Ni and Cr).	[33]
Paper industry	Aluminum	pH 7.0, current density 24.80, treatment time 50 min, with 100 rpm and an electrolyte dose of 1 g/L.	68	The EC process had COD, Color, TOC and TDS removal efficiencies of 68 %, 94 %, 67 % and 37 %.	[53]
printing ink industry	Aluminum	DC of 21 mA/cm^2, electrode spacing of 3mm and, treatment time 120 min	88	The EC process obtained a COD removal rate of 88 %, color 99 %, and TSS reduction of 98 %.	[54]
Sugar industry	Aluminum	pH 7, reaction time of 60 min and electrical power of 10 and 30 V.	*Phosphate 99.38	The EC technique obtained a phosphate removal of 99.38 %.	[55]
Textile industry	Iron	10 electrodes, pH 8.24, electrode spacing 4 mm, voltage 70 V.	90.16	The continuous electrocoagulation-adsorption processes showed a removal of color, COD and TSS of 96.87 %, 89.77 % and 84.46 %.	[56]
Licorice extract powder production industry.	Iron	Electrolysis time of 70 to 90 min and an average DC of 250 to 450 A/m^2.	89.4	The EC technique achieved 90.1 % color removal; COD 89.4 %; turbidity 82 % and alkalinity 73.3 %.	[57]
Industrial Tanneries.	Aluminum	Treatment time 40 minutes and a DC of 6 mA/ cm^2	70	The technique showed a COD reduction of 70%; TSS, chromium (III) and turbidity had a removal greater than 90 %.	[58]
Textile dyeing factory.	Aluminum	Initial pH of 5.5, DC current of 15 mA / cm^2 and an EC time of 23 min	*Color 98	The percentage of decolorization in the wastewater was 98%.	[59]
Oil refinery	Aluminum and stainless steel.	pH 6, current density of 35 mA/ cm^2 and treatment time of 120 min. 90	90	Through the EC process a COD removal of 90 % and a turbidity reduction of 75 % was obtained.	[11]

Note. **Removal** efficiency measured through COD. CD, current density; EC, electrocoagulation; TSS, total suspended solids; TP, total phosphorus; TOC, total organic carbon; BOD, biochemical oxygen dem and *Removal measured through other parameters.

Source: own elaboration

CONCLUSIONS

The electrocoagulation (EC) process has demonstrated remarkable versatility and effectiveness across a wide range of industrial wastewater sources, including the food, dairy, meat, textile, electroplating, rubber, sugar, oil refinery, and paper industries, among others. This adaptability arises from EC's ability to remove various contaminants organic matter, nutrients, heavy metals, dyes, and suspended solids through electrochemical oxidation, coagulation–flocculation, and adsorption mechanisms.

In the food and dairy sector, EC systems using iron electrodes have achieved removal efficiencies of up to 96% for total COD, 95% for soluble COD, and 94% for turbidity, thus demonstrating their strong capacity to remove both particulate and dissolved organic fractions. Likewise, the meat and slaughterhouse industries have benefited from EC combined with anaerobic digestion, achieving reductions above 79% for COD, 95% for nitrates, and 90% for turbidity, confirming its potential as a pre- or post-treatment step to enhance biodegradability and improve effluent quality.

For the textile and dyeing industries, characterized by high loads of persistent dyes and surfactants, EC using stainless steel or aluminum electrodes has achieved COD removal rates between 81% and 90%, and color removal above 98%. These findings indicate that EC efficiently degrades chromophoric groups and complex organic compounds, which are often responsible for the high toxicity and low biodegradability of textile effluents. Similarly, in the printing ink industry, EC achieved 88% COD, 99% color, and 98% TSS removal, which highlights its suitability for treating highly pigmented effluents. The sugar industry has also shown excellent results with EC, achieving up to 97.8% COD and 99.7% color removal when using mixed electrodes (Fe, Al, and Cu) under optimal pH and current density conditions. Additionally, EC has proven effective in removing specific pollutants such as phosphate ions, with efficiencies as high as 99.38%, contributing to the mitigation of eutrophication in receiving water bodies.

In oil refinery wastewater, where high concentrations of hydrocarbons and emulsified oils are common, EC with aluminum and stainless steel electrodes has achieved 90% COD and TSS reduction, even under neutral pH conditions. These results demonstrate that EC effectively destabilizes oil–water emulsions and significantly decreases the organic load, improving the potential for effluent reuse. Other industrial sectors, such as electroplating, have benefited from EC's ability to remove heavy metals (Cu, Zn, Ni, Cr) with efficiencies above 90%, highlighting its role as an eco-friendly alternative to chemical precipitation. Likewise, in the fishing and poultry processing industries, EC achieved simultaneous removals of COD (93%), BOD (97%), turbidity (97%), and oils and fats (94%), considerably improving overall water quality.

From an environmental perspective, electrocoagulation is emerging as a sustainable alternative for industrial wastewater treatment. Unlike conventional chemical coagulation, this process generates smaller volumes of less toxic sludge, facilitating final disposal and even enabling its potential valorization. Additionally, the treated effluent achieves sufficient quality for reuse in irrigation or industrial cleaning, promoting water circularity particularly in regions facing water stress. However, large-scale implementation still presents technological and economic challenges. Electrode passivation, energy consumption, and the lack of standardization in reactor designs are barriers that require attention. To overcome them, it is strategic to integrate electrocoagulation with complementary technologies such as advanced oxidation processes, bioelectrochemical systems, or renewable energy sources along with developing predictive models and life cycle assessments that quantify its environmental benefits. In this way, electrocoagulation can definitively position itself as a clean, efficient, and sustainable technology for the comprehensive management of industrial wastewater.

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DOI: https://doi.org/10.14483/22487638.22943

REVISIÓN

Emerging Trends in Business Intelligence: A systemic Mapping Study

Tendencias emergentes en Inteligencia de Negocios: Un Mapeo Sistémico

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Fecha de Recepción: 25 de noviembre de 2024 **Fecha de Aceptación:** 1 de diciembre de 2025

Cómo citar: J. F. Hernández-Castro, G. Caceres-Castellanos, J. S. González-Sanabria (2025). Tendencias emergentes en Inteligencia de Negocios: Un Mapeo Sistémico. *Tecnura*, 29(86), 100–128. https://doi.org/10.14483/22487638.22943

Abstract

Objective: The study aims to conduct a systematic mapping of emerging trends in business intelligence (BI) by analyzing research published between 2017 and 2024, in order to identify patterns, influential authors, key sectors, and future research opportunities.

Methodology: We used the systematic mapping methodology described by Kitchenham, including two iterations of searches in academic databases such as Scopus, IEEE Xplore, and Web of Science. The collected data (1504 studies) were analyzed using tools such as VOSviewer and Microsoft Excel, focusing on network maps, overlays, and density visualizations to interpret key patterns and relationships.

Results: The analysis revealed dominant trends such as the use of big data, machine learning, predictive analytics, and real-time BI. Geographically, Asia and the Middle East lead in publications, with strong BI adoption in sectors such as healthcare, education, and retail. Less explored areas were also identified, such as the integration of BI with the Internet of Things, advanced social network analytics, and data ethics.

Conclusions: This study concludes that BI continues to evolve towards more advanced and ethically responsible technologies, with a focus on personalization and real-time decision-making. Less explored areas represent opportunities for future research, particularly regarding data governance and the integration of BI in specific sectors. This work provides a comprehensive overview of the current state of BI research and suggests strategic directions for its development.

***Keywords*:** business intelligence, emerging trends, systematic mapping, VOSViewer

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Resumen

Objetivo: Este estudio tiene como objetivo realizar un mapeo sistemático de las tendencias emergentes en inteligencia de negocios (BI), analizando investigaciones publicadas entre 2017 y 2024, para identificar patrones, autores influyentes, sectores principales y oportunidades futuras de investigación.

Métodología: Se utilizó la metodología de mapeo sistemático descrita por Kitchenham, incluyendo dos iteraciones de búsqueda en bases de datos académicas como Scopus, IEEE Xplore y Web of Science. Los datos recopilados (1504 estudios) fueron analizados mediante herramientas como VOSviewer y Microsoft Excel, con énfasis en mapas de red, superposición y densidad para interpretar patrones y relaciones clave.

Resultados: El análisis reveló tendencias predominantes, como el uso de big data, machine learning, análisis predictivo y BI en tiempo real. En términos geográficos, Asia y Medio Oriente lideran en publicaciones, con una fuerte adopción de BI en sectores como salud, educación y comercio minorista. También se identificaron áreas menos exploradas, como la integración de BI con el Internet de las Cosas, la analítica avanzada de redes sociales y la ética en el manejo de datos.

Conclusiones: El estudio concluye que BI sigue evolucionando hacia tecnologías más avanzadas y éticamente responsables, con un enfoque en la personalización y la toma de decisiones en tiempo real. Las áreas menos investigadas representan oportunidades para futuras investigaciones, particularmente en la gobernanza de datos y la integración de BI en sectores específicos. Este trabajo ofrece una visión integral del estado actual de la investigación en BI y sugiere direcciones estratégicas para su desarrollo.

***Palabras clave*:** inteligencia de negocios, tendencias emergentes, mapeo sistémico, VOSViewer

Introduction

In today's business landscape, business intelligence (BI) has become indispensable for strategic decision-making, allowing organizations to adapt to the changing environment through data analysis [1]. BI has undergone a great evolution, driven by emerging trends such as artificial intelligence (AI) and machine learning (ML), with applications in various industries [2].

Despite the growing interest, there are still knowledge gaps regarding the way in which these trends integrate and change business practice. This systematic mapping, which encompasses journal articles, conferences, and books, primarily aims to provide an overview of the current BI research landscape and identify areas of opportunity for future research. Through a bibliometric and geographical analysis, it seeks to answer the following questions:

- What are the main emerging trends in BI?
- Which authors and regions are leading research in this field?
- Which sectors are adopting BI more frequently?
- Which areas of BI research remain unexplored?

The analysis of these questions will identify the most recent advances in BI, the key players, the areas of greatest interest, and the gaps in the current literature, laying the groundwork for future research.

Methodology

This study identifies literature on emerging trends in business intelligence which were published between 2017 and 2024, using a systematic mapping methodology. Following Kitchenham's framework [3, 4], our work is divided into five stages that cover planning (defining research questions and search strategies), execution (selecting studies), and the presentation of results.

Definition of research questions

The following research questions were defined to guide this systematic literature review:

- Q1: What are the main emerging trends in BI in recent years?
- Q2: Who are the most influential authors in the field of BI?
- Q3: What is the geographic distribution of BI publications and their emerging trends?
- Q4: What sectors or industries are using BI the most?
- Q5: What are the least explored areas in BI research?

Search protocol

The literature search was conducted in two iterations using academic databases such as Scopus, EBSCO, Web of Science, IEEE Xplore, Springer, and ScienceDirect. In the first iteration, we searched for articles published in English or Spanish between 2017 and 2024 which included key terms such as *business intelligence* and *emerging trends* in the title, abstract, or keywords. The search string used was:

(TITLE(business-intelligence) OR TITLE-ABS-KEY(emerging-trends-in-business-intelligence) OR TITLE-ABS-KEY(bi-trends)) AND PUBYEAR > 2016 AND PUBYEAR < 2025 AND (LIMIT-TO(LANGUAGE, "English") OR LIMIT-TO(LANGUAGE, "Spanish"))

In the second iteration, the results were refined to focus on the most relevant emerging trends, as shown in the example search string for *cloud-business-intelligence*:

(TITLE (business-intelligence) AND TITLE (cloud-business-intelligence)) AND PUBYEAR > 2016 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE , "English") OR LIMIT-TO(LANGUAGE, "Spanish")) AND (LIMIT-TO (EXACTKEYWORD , "Business Intelligence"))

Inclusion and exclusion criteria

For the first iteration, based on a total of 6832 search results, 1504 potential studies were selected for detailed review using a set of inclusion and exclusion criteria, which are illustrated in Table I for this first iteration.

The second iteration focused exclusively on further exploring the most relevant trends identified during the first review phase. As a result of this process, 51 papers were selected which met the specific inclusion criteria.

Table I. Inclusion and exclusion criteria for the first iteration

Inclusion criteria	**Exclusion criteria**
• Publications on BI trends in various industries • Studies on the exploration of new technologies in BI • Articles about emerging trends in BI • Articles in English or Spanish • Open-access papers • Articles that have been published in their final version and conferences related to the subject of the study	• Duplicate articles • Opinion articles • Studies not directly related to BI applications • Studies with publication dates outside the 2017-2024 range

Classification of studies

The selected studies were classified into emerging technologies, industrial applications, methodologies, and topics related to their implementation (Fig. 1). Social network analysis and the Internet of Things (IoT), along with system integration and BI tools, were the most researched topics (with eight publications each), reflecting the interest in connectivity and real-time data analysis. Predictive analytics, ML, AI, big data, and data analytics were also relevant. In contrast, data storytelling and data ethics and governance had fewer publications, suggesting areas with potential for future research.

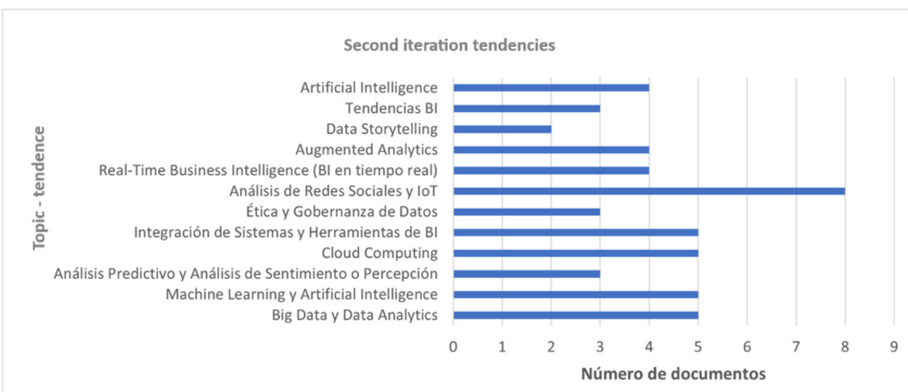

Figure 1. Analysis of emerging issues in the second iteration

Results analysis

The results of the two search iterations, exported in RIS files, were analyzed with VOSviewer and Excel. The geographic information in the files was cleaned to analyze the location of the publications.

To identify trends, authors, technologies, and research areas, the data were categorized and visualized with VOSviewer [5, 6], a tool that facilitates the understanding of patterns in the scholarly literature.

Results

Distribution of publications in the first iteration

In the first iteration, 1504 studies on BI trends from various academic databases were reviewed. Below is the distribution of publications among the different sources:

- **Scopus**. With 563 publications (37.4% of the total), Scopus represents the main source of information. Its broad coverage makes it a key database for the analysis of trends and emerging topics in BI.
- **IEEE Xplore.** Ranked second with 353 publications (23.5% of the total), its focus on engineering and technology makes it relevant for research linking BI with technological aspects.
- **Web of Science (WOS) and Springer.** Both databases exhibit a similar number of publications, with 236 and 231 articles, respectively (15.7 and 15.4% of the total). They offer a variety of academic studies in multiple disciplines, which brings a diverse perspective to the analysis.
- **EBSCO.** With 81 publications (5.4%), EBSCO can be considered a secondary source in terms of volume, but it is relevant for broadening the academic context.
- **ScienceDirect.** This database offers 40 publications (2.7% of the total). Although its contribution is lower compared to the others, its focus on scientific articles adds value to the review.

Together, Scopus and IEEE Xplore account for more than 60% of the analyzed publications, consolidating their position as the most influential databases in this study on BI trends. Fig. 2 summarizes the total number of publications under analysis and provides a visual representation of their distribution by source, which facilitates the interpretation of the data and the identification of the main sources for future research in this field.

Analysis of the second iteration

An analysis of the 51 papers selected in the second iteration revealed that emerging trends in BI are being actively explored, particularly those related to network connectivity and advanced data analytics. The growth in the number of publications over the years is evidence of the importance and dynamism of this research area. Likewise, the distribution of publications by type highlights the fundamental role of journals and conferences in the dissemination of knowledge.

Analysis of publications by year

Fig. 3 shows a steady growth in the number of publications since 2017, with a notable increase between 2021 and 2023. This increase reflects a growing interest in emerging trends in BI. While a decrease in the number of publications is observed in 2024, this may be due to the year not yet ending or a possible stabilization in the field.

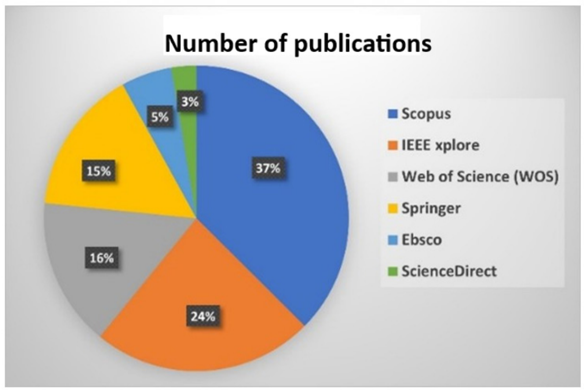

Figure 2. Number of publications per database, first iteration

Figure 3. Publications by year, second iteration

Distribution of publications by type

Fig. 4 shows that most of the publications correspond to journal articles (30), indicating that academic journals are the main means for disseminating research in this area. Conference papers (16) are also frequent, suggesting that the topic is actively discussed at academic events. On the other hand, books and book chapters are less common, which is usual, as they usually represent compilations or more extensive studies compared to journal or conference articles.

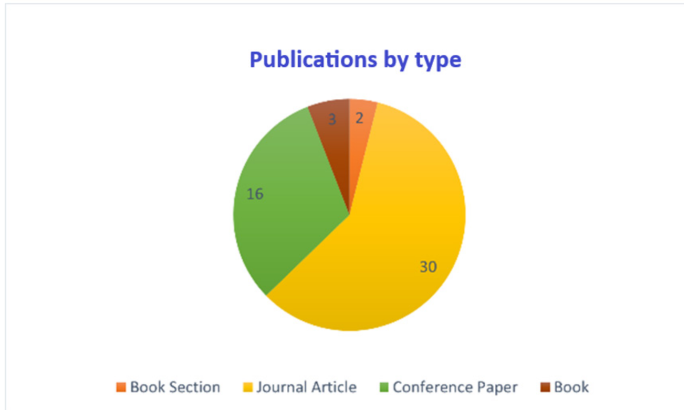

Figure 4. Publications by type, second iteration

Fig. 5 shows the network of keywords related to BI, which was generated in VOSviewer [7, 8] for the first iteration. This figure allows identifying several emerging trends and key areas that are gaining relevance in this field. These trends are also reflected in the second iteration. A detailed analysis of the observed trends is presented below.

R1. What are the main emerging trends in BI in recent years?

BI as the central core: In Fig. 5, BI is placed at the center of the network, reflecting its fundamental role and its interconnection with other topics. The high frequency of occurrence of this term indicates its importance and extensive study in literature.

Big data and data analytics: The size of the big data and data analytics nodes suggests that these are important areas of research. Both are closely linked with BI, indicating that the integration and analysis of large volumes of data are essential for the development of modern BI [9, 10].

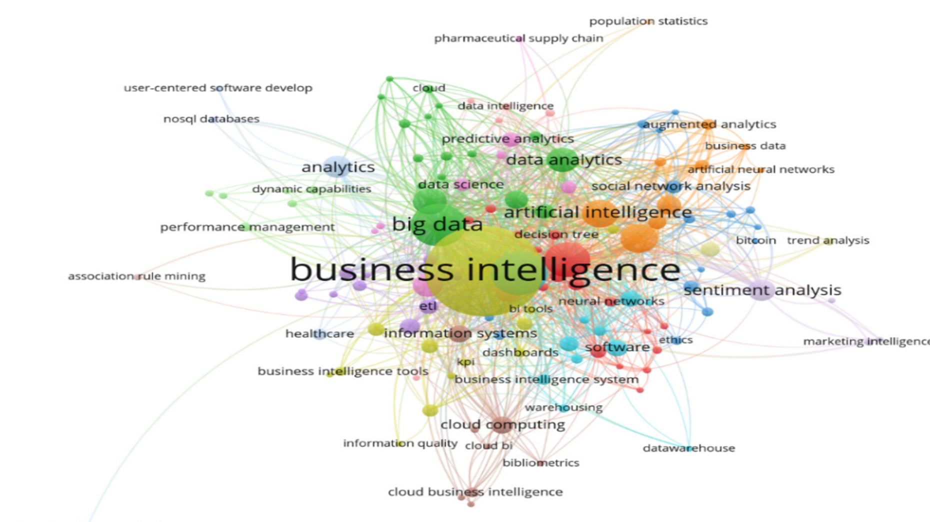

Figure 5. Network visualization

The convergence of big data and BI has allowed companies to analyze and extract value from large volumes of data that were previously inaccessible [11, 12]. Technologies such as Hadoop and Spark are being integrated into BI platforms to handle, process, and analyze big data, enabling more comprehensive and large-scale analysis [13]. At the educational and social level, this is a tool that allows for analysis from various perspectives of great importance, which would be complex with traditional approaches. Thus, with the help of technology, barriers can be overcome, and agile solutions can be found [14].

ML and AI: These terms exhibit direct connections to BI, reflecting the growing use of ML algorithms and AI techniques to improve real-time decision making and predictive analytics in enterprises. These technologies are being deployed to extract patterns and trends in data, supporting the digital transformation. The integration of AI and ML into BI has made it possible to automate and improve the accuracy of data analytics [15, 16, 17]. AI capabilities, including those related to natural language processing (NLP) and sentiment analysis, are allowing enterprises to extract deeper insights and process unstructured data, such as text and videos, more efficiently [18, 19, 20].

Predictive analytics and sentiment analysis: In the keyword network, the presence of the predictive analytics and sentiment analysis in connection to BI indicates a growing interest in these areas. Predictive analytics is used to anticipate future behaviors, while sentiment analysis provides a better understanding of public opinion and customer satisfaction [21, 22].

Predictive and sentiment analytics: This branch of BI uses historical data to predict future outcomes, *e.g.*, in forecasting high-risk events [18]. ML tools and techniques have enabled a greater integration of predictive analytics into BI platforms. This makes it easier for companies to anticipate market trends, demand, customer feedback, and potential operational issues [17, 19].

Prescriptive analytics: This area goes a step beyond prediction by suggesting specific actions to obtain the best results [18]. This trend is booming in the BI field since it helps organizations make more informed and optimized decisions.

Cloud computing: The presence of *cloud computing* and related terms, such as *cloud business intelligence*, in the keyword network indicates the increasing migration of BI applications to the cloud. This trend offers more flexible access to data and improves organizations' ability to analyze and share information in real time. The rise of cloud computing has driven the adoption of cloud-based BI solutions, which offer flexibility, scalability, and lower costs compared to on-premises solutions [23]. In addition, they allow companies to access data and analytics from anywhere, which facilitates remote working and global collaboration [24], [25]. The COVID-19 pandemic accelerated the adoption of the cloud as a management decision support tool that employs BI tools. The use of BI to analyze market trends and consumer behavior allowed organizations to adjust their strategies and remain competitive despite the economic constraints and changes [26].

Integration of BI systems and tools: The presence of terms such as *information systems*, *dashboards*, and *data visualization* in the keyword network highlights the importance of information systems and visualization tools in the BI ecosystem. These tools are essential to facilitate data interpretation and strategic decision-making [27, 28]. In particular, data visualization tools in BI allow transforming large volumes of information into interactive graphs, maps, and dashboards that facilitate quick and clear understanding [29, 30].

Ethics and data governance: Although not among the most prominent topics, the presence of these terms in the keyword network indicates a growing concern for ethics and data governance in the realm of BI. This topic becomes relevant as the intensive use of data raises challenges related to privacy and the responsible use of information. The increased use of data in BI has driven concerns about data ethics and data governance [31] Companies are adopting more rigorous practices to ensure the ethical use of data and compliance with privacy regulations, such as the General Data Protection Regulation (GDPR) [32]. This trend promotes a greater focus on transparency, data quality, and protection of user privacy [33], [34].

Social network analysis and IoT: The presence of these terms in the keyword network signals a trend towards integrating data from social networks and connected devices into BI strategies. This allows companies to gain valuable insights from a wider range of sources. Social networks and the IoT generate a wealth of data that companies are beginning to leverage through BI [35, 36]. Social network analysis enables a better understanding of customers and the prediction of trends [37, 38], while the integration of IoT data into BI provides insights into device behavior and operational processes [39, 40].

Real-time BI: The presence of this trend in the keyword network confirms the growing importance of the ability to analyze real-time data in the field of BI. In dynamic business environments, real-time analytics allows organizations to react with agility to market changes, optimize operational decision-making and maintain a competitive edge [41]. This capability is especially valuable in sectors that require rapid responses, such as healthcare [42], e-commerce, finance, and logistics [43]. Real-time BI is supported by streaming data processing technologies and the use of cloud platforms, as seen in the connection with cloud computing nodes. Access to real-time data and analytics is no longer a luxury but a necessity in many industries [44]. Today's BI platforms allow monitoring live data, making it easier for companies to react with immediacy to events and changes in the market [45]. This capability is crucial in industries such as finance, where real-time decisions can have a significant impact [46].

Augmented analytics: This is an emerging trend in the keyword network. It combines AI, ML, and NLP to optimize traditional analytical processes. Thus, it helps users to discover insights in an automated way and reduce dependence on specialized data analysts, democratizing access to BI [47]. By automating analytical tasks and generating actionable recommendations, augmented analytics facilitates faster and more accurate interpretation of data, which is crucial for responding to dynamic changes in the business environment [48], [49]. Augmented analytics combine BI with AI and ML to optimize data analysis and decision-making. This trend is characterized by the use of automated tools to clean, analyze, and visualize data, which reduces reliance on data analysts and allows business users to interact directly with information [50].

Data storytelling: Although this trend does not appear explicitly in the keyword network, it is a crucial emerging trend in the field of BI, especially in terms of data visualization and presentation [51]. Data storytelling involves the ability to translate complex analytics into understandable and relevant narratives for decision making [52]. This trend is linked to the use of dashboards, data visualization, and information systems (themes present in the network) and is critical to ensure that findings are understood and used effectively at all levels of an organization. Data-driven storytelling is especially useful in business contexts to create compelling, evidence-supported presentations.

Temporal evolution of keywords

Fig. 6 presents an overlay visualization [40, 53] that allows analyzing the temporal evolution of keywords. The color bar at the bottom of the figure shows a gradient of years (2019-2022), which facilitates the identification of changes in the popularity of certain keywords. Terms in blue shades represent concepts whose discussion started before 2019, while green and yellow shades correspond to more recent concepts.

For example, terms such as *pharmaceutical supply chain* and *population statistics*, represented in yellow, have become more relevant in recent years, possibly in the context of the pandemic.

As for emerging trends, terms such as *ethics* and *blockchain* are located on the periphery of the network, which could indicate that they are growing topics but do not yet occupy a central place in BI. Likewise, the presence of *marketing intelligence* and *trend analysis* points to an emerging interest in these subfields.

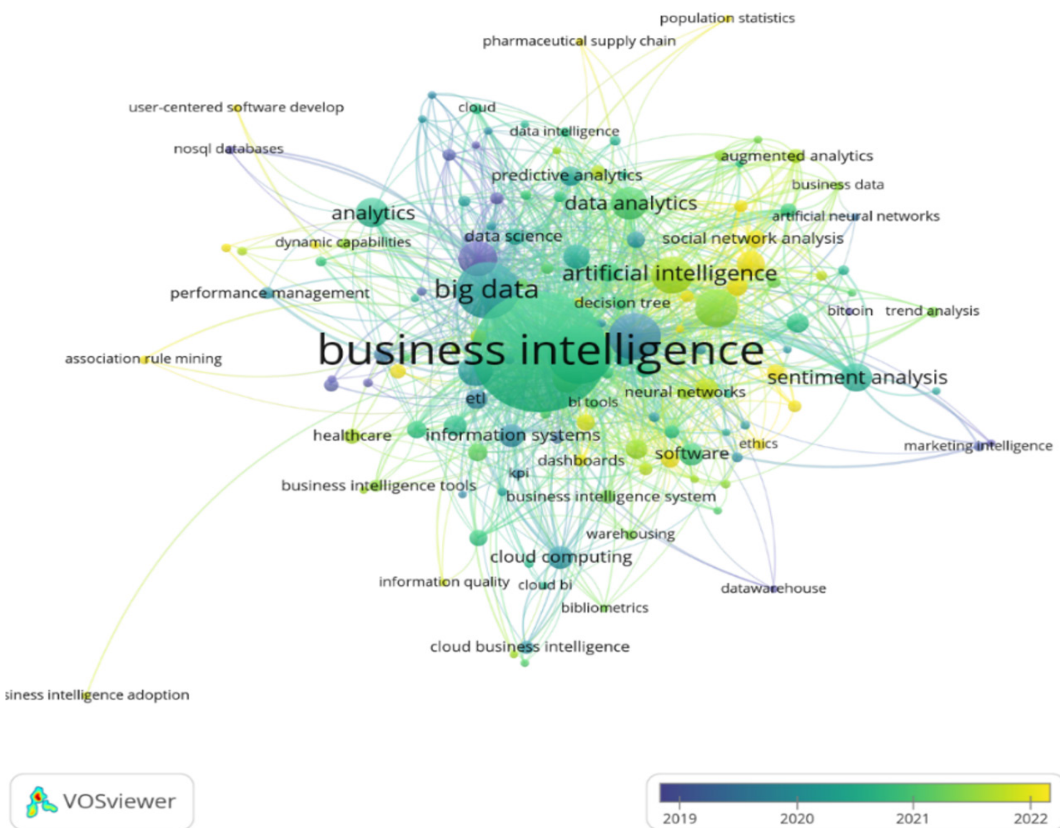

Figure 6. Overlay visualization

R2. Who are the most influential authors in the field of BI?

According to the visualizations, the most influential authors in the field of business intelligence are G. Szárnyas, P. Boncz, and Y. Zhang. These researchers are noted for the following aspects:

Production volume: The density visualization (Fig. 7) shows that Szárnyas and Boncz are in high-density areas, indicating a high frequency of publications in this field. This suggests that they have contributed significantly to the literature, positioning themselves as key authors.

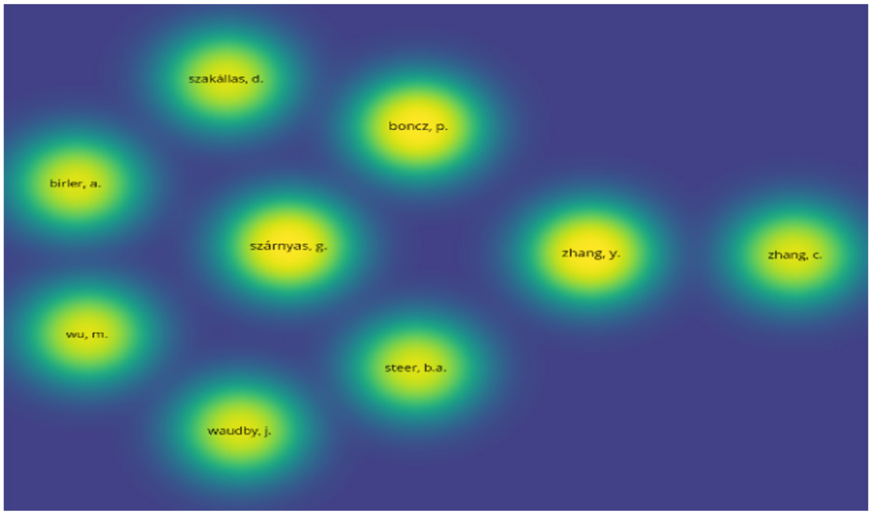

Figure 7. Density visualization – authors

Network collaboration: Fig. 8 shows a network visualization in which these same authors appear connected to a dense network of co-authorships, evidencing a strong collaboration between them. Their joint work could be a fundamental pillar in recent research and developments in BI.

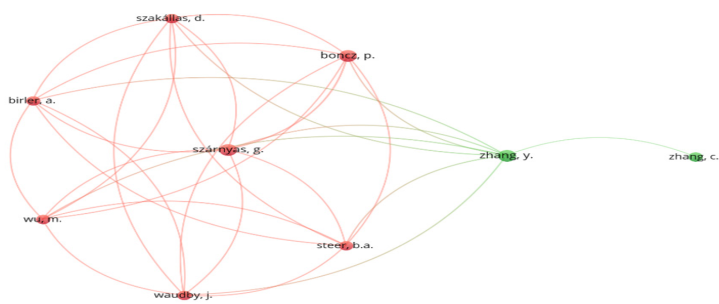

Figure 8. Network visualization – authors

News and trends: In the overlay visualization (Fig. 9), Zhang is positioned as one of the authors with recent publications, indicating that he is at the forefront of current research and emerging trends in the field of BI.

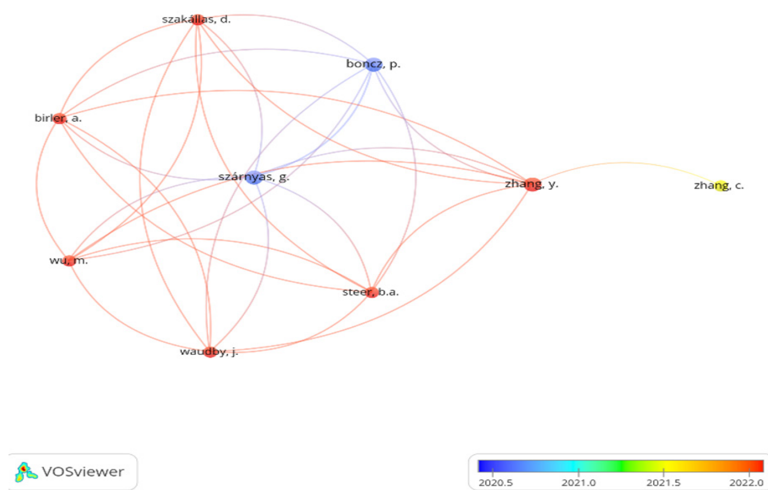

Figure 9. Co-authorship overlay visualization

In conclusion, the analysis performed with the VOSviewer tool reveals that Szárnyas, Boncz, and Zhang stand out as the most influential authors in BI research, leading both in scientific production and collaboration within the academic community.

R3. What is the geographic distribution of BI publications and their emerging trends?

Fig. 10 shows the geographical distribution of publications related to BI and its emerging trends in different countries. An analysis of this distribution is presented below.

The analysis of the geographical distribution of publications (Fig. 10) reveals the following:

Leading regions:

- *Asia and Middle East:* India (55 publications), Malaysia (38), Saudi Arabia (24), China (24), and Indonesia (31) lead the list. This suggests a strong interest in BI in these regions, possibly driven by accelerated growth in technology and BI adoption in key sectors such as retail and manufacturing.
- *Americas:* The United States (36 publications) stands out in the Americas, followed by Mexico (7), Colombia (9), and other Latin American countries. This indicates that, although there is considerable interest in BI in the region, its development is concentrated in certain areas.
- *Europe:* Countries such as Spain (33 publications), Portugal (19), Greece (18), England (17), Italy (17), and France (15) show a strong presence, which is evidence of a solid interest in BI in Europe. Nordic countries such as Finland (13) and Norway (9) also contribute, possibly due to their focus on digitization and technology.

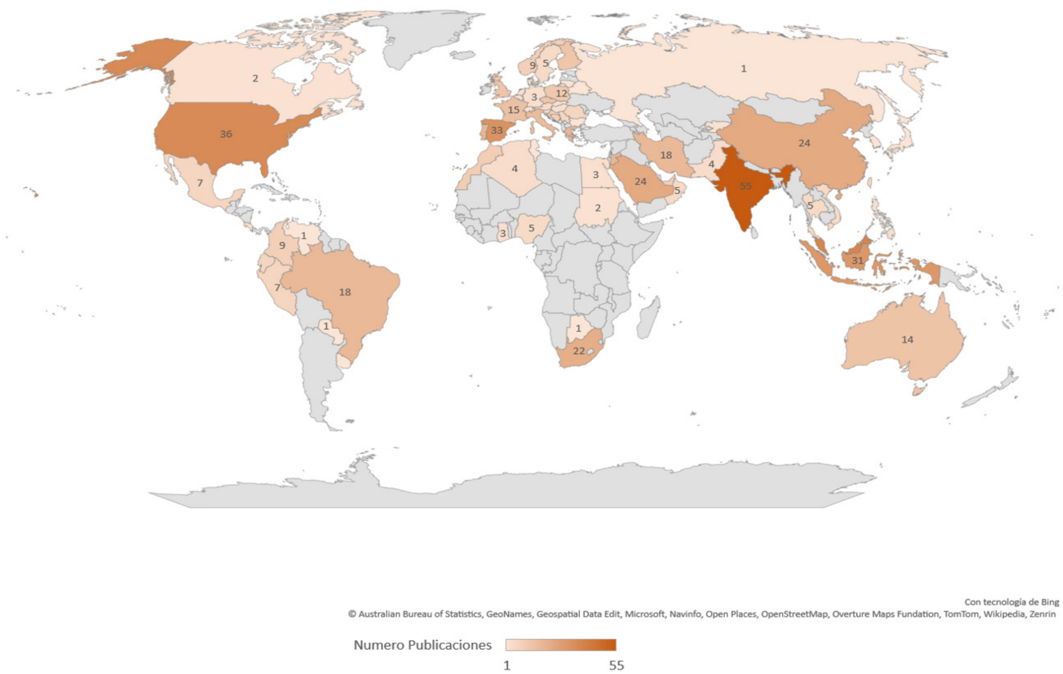

Figure 10. Geographic distribution of publications

Emerging countries in BI:

- *Africa:* South Africa (22 publications) leads in the continent, followed by Morocco (10) and Nigeria (5). This suggests that some African countries are embracing BI, especially in sectors such as finance and telecommunications.
- *Latin America:* Countries such as Brazil (18 publications), Colombia (9), Mexico (7), Ecuador (7), and Peru (7) show a growing interest in BI, reflecting the development of data technology in the region.

R4. What sectors or industries are using BI the most?

The analysis of keywords associated with BI reveals the sectors or industries with high adoption rates. A detailed analysis of these associations is presented below.

Sectors with the highest adoption of business intelligence

In Fig. 11, which presents a density visualization, the keywords appearing in the highest density region (bright yellow) are:

- Social media (social networking)
- Cloud computing

- Analytics
- Healthcare
- Education

This suggests that BI is most frequently used in these sectors, probably in order to leverage large volumes of data and optimize decision-making.

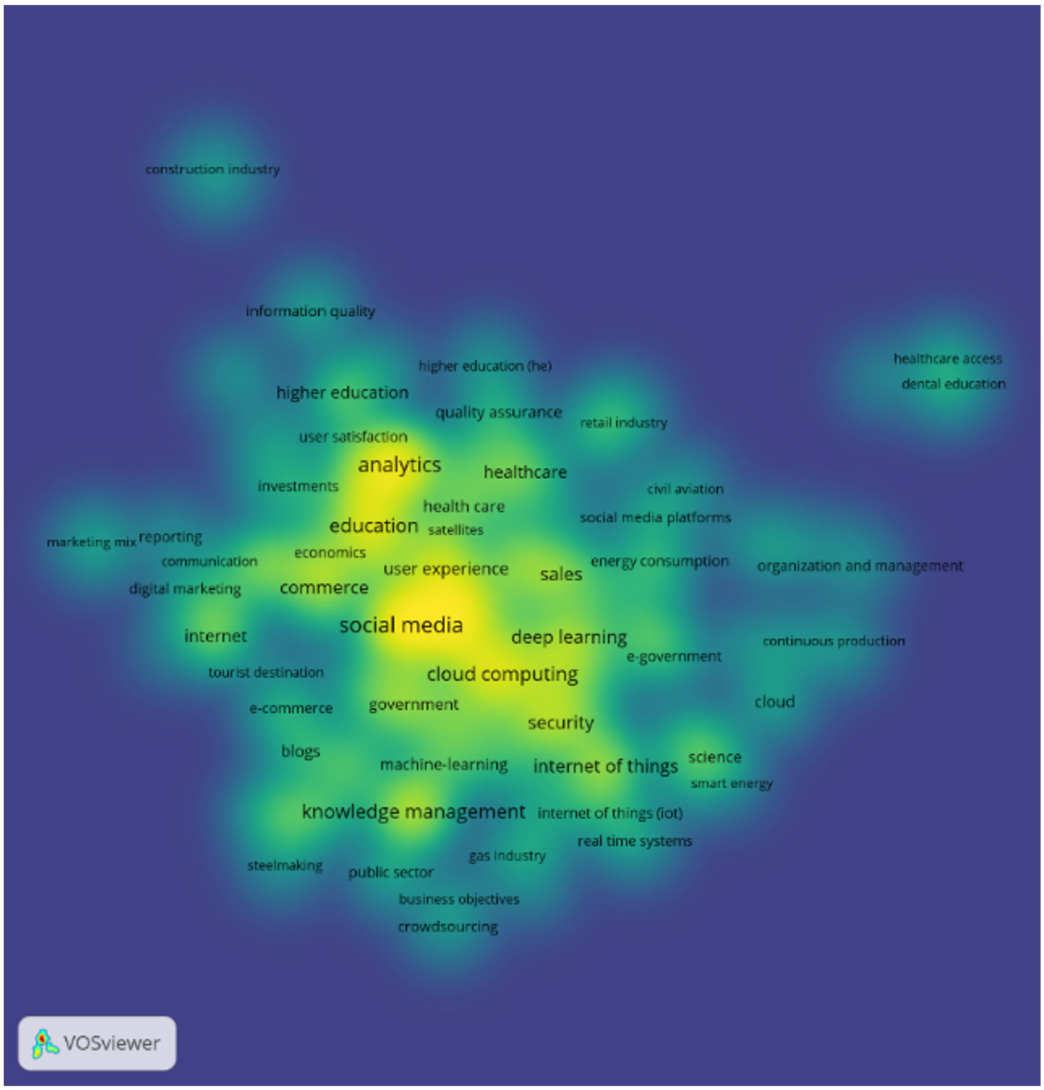

Figure 11. Density visualization, industries with BI adoption

Relationship between sectors and BI

The network visualization presented in Fig. 12 shows detailed connections between the terms, allowing for the identification of specific sectors and application areas where BI interrelates with other areas. Key sectors connected to analytics and cloud computing include:

- *Healthcare:* connections to themes such as *quality of life* and *digital health* suggest that BI in this sector is focused on improving efficiency in clinical and patient data management.
- *Retail:* Linkages with *user experience* and *social media* indicate that BI is used in retail to optimize customer interaction and maximize sales.
- *Education:* The link with *higher education* and *user satisfaction* indicates that BI is used to improve educational services and adapt content to the needs of students.
- *E-commerce and digital marketing:* The strong connection with *social media* and the *Internet* suggests that BI is used to analyze customer data and personalize the online shopping experience.

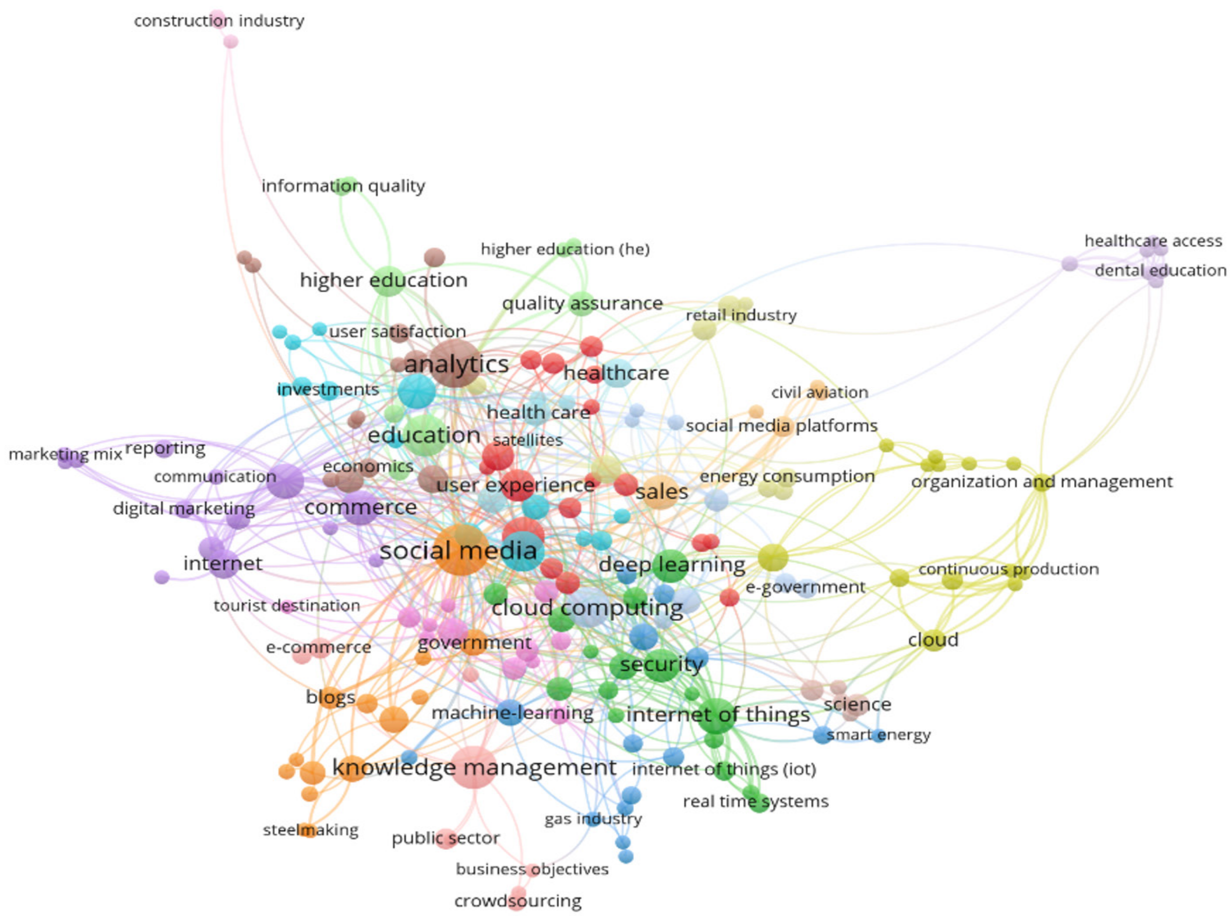

Figure 12. Network visualization, industries with BI adoption.

Temporal evolution of trends in specific sectors

The temporal overlay visualization presented in Fig. 13 allows identifying emerging trends in various sectors over time. The most recent keywords (marked in green and yellow) include

- Internet of Things (IoT)
- Machine learning

- Deep learning
- Smart energy

These terms indicate that, in recent years, BI has become more relevant in sectors such as smart energy and the IoT, where connectivity and advanced data analytics are being used to improve efficiency and sustainability.

R5. What are the least explored areas in BI research?

To identify the least explored areas in business intelligence research, the network (Figure 12), overlay (Figure 13) (previously presented) and density (Figure 14) visualizations were analyzed.

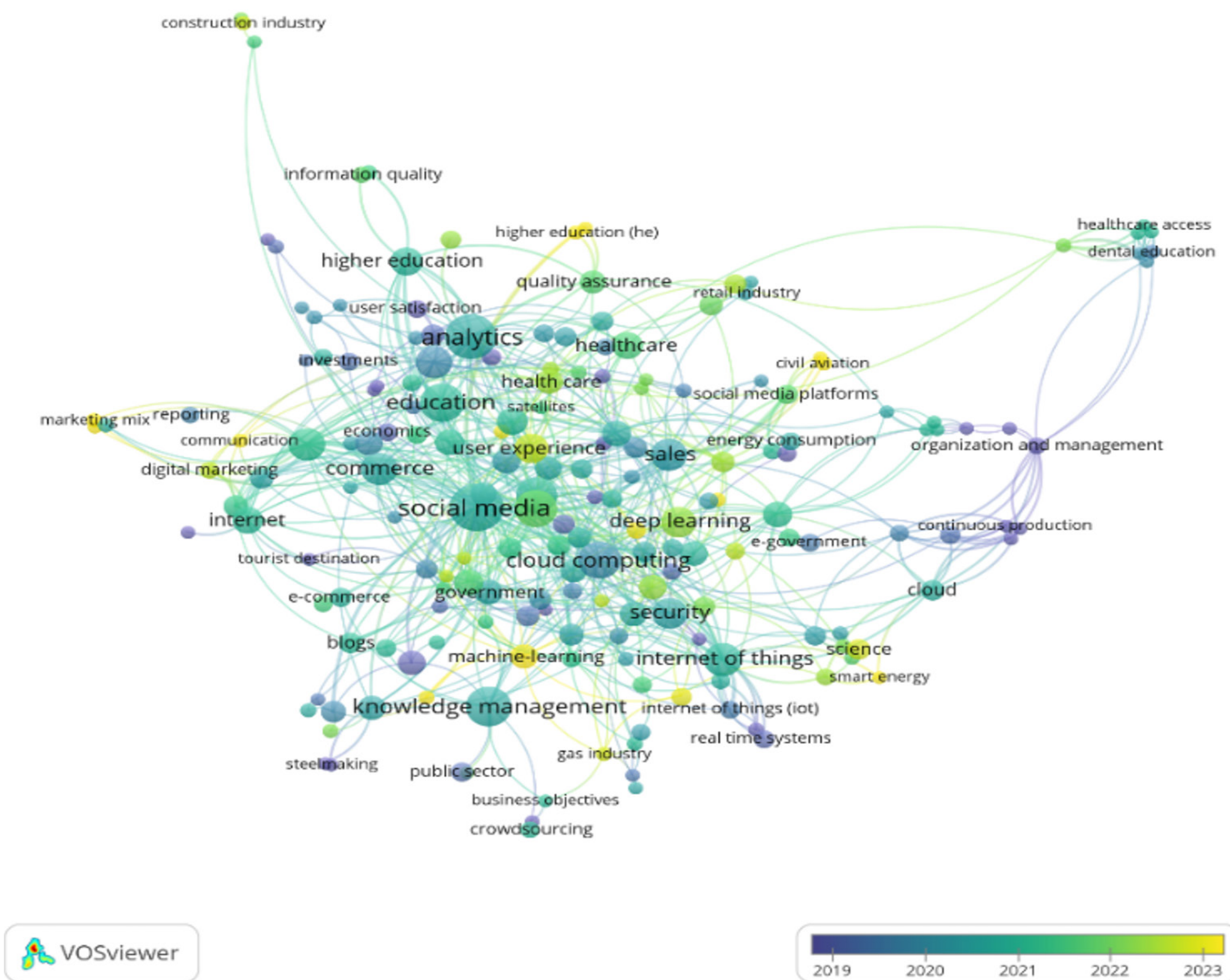

Figure 13. Overlay visualization, industries with BI adoption

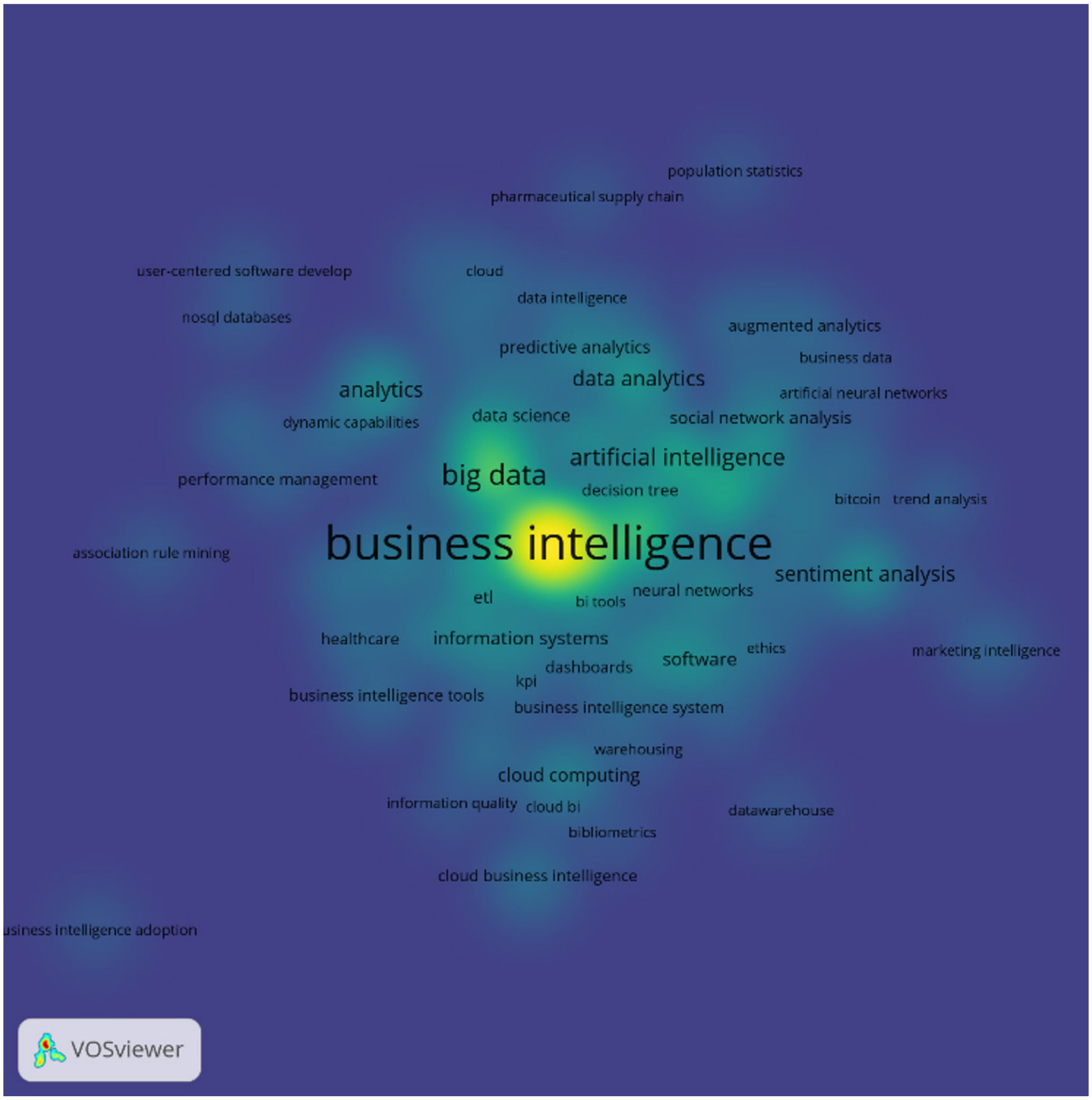

Figure 14. Keyword density display

Analysis of less explored areas

To identify the least explored areas in BI research, network (Fig. 12), overlay (Fig. 13), and density visualizations (Fig. 14) were analyzed.

Network visualization analysis

Fig. 12, which presents a network visualization, shows a set of connected terms around BI. Among the main concepts, which are in the center of the map, with a high density of connections, *big data*, *data analytics*, *artificial intelligence*, and *cloud computing* stand out. This indicates that they have been extensively researched and that there is a close relationship between them.

On the other hand, terms located in the peripheral areas of the map, with a lower density of connections, include:

- *Decision intelligence:* While this term, which combines BI, AI, analytics, and automation to optimize decision-making, is emerging as an evolution of traditional BI, its lack of visibility and connections in the maps suggests that it has not yet been widely explored or adopted in academic or practitioner research.
- *Pharmaceutical supply chain:* This term appears isolated and with few connections, indicating a limited exploration of BI in this specific sector.
- *User-centered software development*: The relationship between this term and BI does not appear to be a frequent area of research.
- *Ethics:* Although it is a relevant topic, its peripheral position in the network indicates that it is an under-addressed perspective in the context of BI.
- *Bitcoin and blockchain:* While the term *bitcoin* is mentioned, it has few connections, suggesting a limited focus on how these emerging technologies could be integrated into business intelligence.

Analysis of the overlay display

The overlay visualization (Fig. 13) provides a temporal perspective, with the colors indicating the average year of occurrence of the terms (from 2019 to 2022). Terms in yellow, representing more recent research, include concepts such as *artificial neural networks*, *augmented analytics*, and *sentiment analysis*. In contrast, areas in blue and green show topics that are less explored or are connected to less recent research works.

Areas that have been less researched in recent years include:

- *Association rule mining:* Although a common technique in data mining, its application in BI appears to be limited.
- *User-centered software development and pharmaceutical supply chain:* These continue to appear as peripheral terms with less relevance in recent research.

Density analysis

The density visualization (Fig. 11) highlights the areas with a high concentration of research. BI, big data, and data analytics appear in bright yellow, indicating that they are widely researched terms.

Terms shown in duller colors or in less dense areas (*i.e.*, less researched areas) are:

- *Pharmaceutical supply chain and association rule mining:* these terms have low density and appear to be areas with less attention in BI research.
- *Ethics and marketing intelligence:* Although these are important areas in practice, they exhibit a lower density, suggesting a lack of significant research at their intersection with BI.

Discussion

Summary of findings and scope of the study

This systematic mapping study provides an updated and structured overview of emerging trends in BI research between 2017 and 2024. In contrast to previous bibliometric and scientometric reviews that cover long historical periods, this study deliberately focuses on recent developments, allowing for the identification of current dominant paradigms, emerging application domains, and research gaps that have not yet consolidated in the literature.

Beyond synthesizing existing studies, this work contributes by structuring the BI research landscape through a multi-dimensional perspective, integrating technological trends, geographic distribution, sectoral adoption, and underexplored research areas within a single analytical framework.

Discussion of results by research question

RQ1 – emerging trends in business intelligence

The results confirm a clear shift in BI research from traditional descriptive reporting towards paradigms of advanced analytics, including augmented analytics, ML, AI, and real-time analytics. This evolution reflects a transition from retrospective data analysis to predictive and prescriptive decision-making (Fig. 15).

A key contribution of this study lies in highlighting augmented analytics as a central trend. Unlike earlier reviews that emphasized ML or data mining in isolation, this mapping shows how augmented analytics integrates AI, automation, and NLP to democratize BI, allowing non-technical users to interact directly with analytical systems.

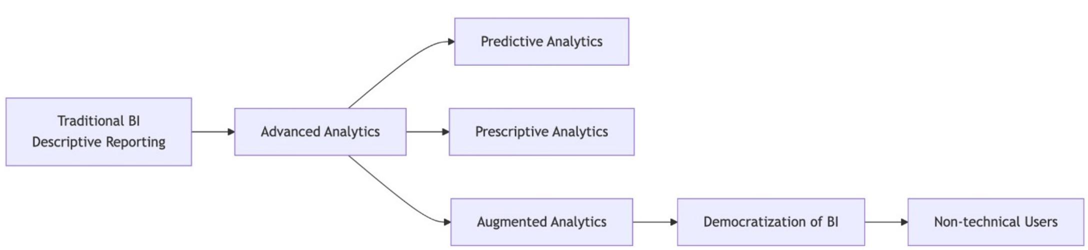

Figure 15. Evolution of BI towards augmented analytics and democratization

This study consolidates dispersed evidence to position augmented analytics not as a peripheral innovation, but as a core evolutionary stage of BI, clarifying its role in expanding adoption beyond technical experts.

RQ2 and RQ3 – authors and geographic distribution

The analysis of authorship and geographic distribution reveals that BI research is primarily driven by institutions in Asia, Europe, and North America, while also showing a growing contribution from emerging economies in Latin America and Africa (Fig. 16).

While previous reviews reported similar regional dominance, this study adds value by demonstrating that recent BI research growth is increasingly global, driven by cloud computing, open-source analytics platforms, and digital transformation initiatives that lower entry barriers.

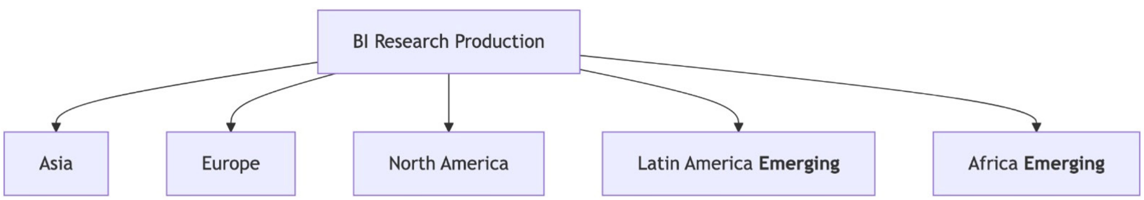

Figure 16. Geographic distribution of recent BI research and emerging regions

This study provides updated empirical evidence that BI research is no longer geographically concentrated, but is undergoing a process of global diffusion, which has implications for future cross-regional collaboration and contextualized BI applications.

RQ4 – BI adoption across sectors

The findings confirm that healthcare, education, retail, and digital marketing remain the sectors with the highest BI adoption. However, a relevant contribution of this mapping is the identification of new and rapidly emerging application domains, particularly smart energy systems and IoT-enabled environments (Fig. 17).

This indicates that BI is evolving from a managerial decision-support tool into a foundational component of cyber-physical and data-intensive ecosystems, where real-time data streams and automation are critical.

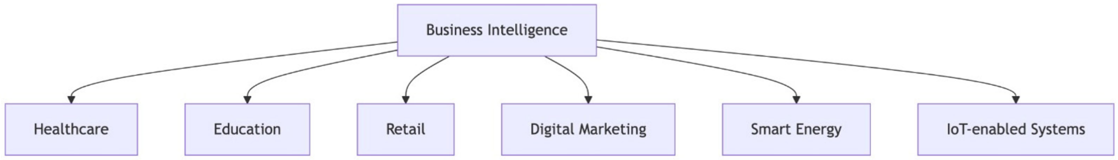

Figure 17. Sectoral distribution of BI applications identified in the mapping study

Our work goes beyond descriptive mapping by explicitly framing these gaps as research opportunities, providing a structured agenda for future BI research that balances technological advancement with ethical and human-centered considerations.

Beyond providing a descriptive synthesis of the literature, this systematic mapping makes explicit contributions to the field of BI. These contributions are articulated along four dimensions (temporal, conceptual, contextual, and strategic) that collectively differentiate this study from previous bibliographic reviews. Figs. 18 and 19 summarize these contributions and their implications for future BI research.

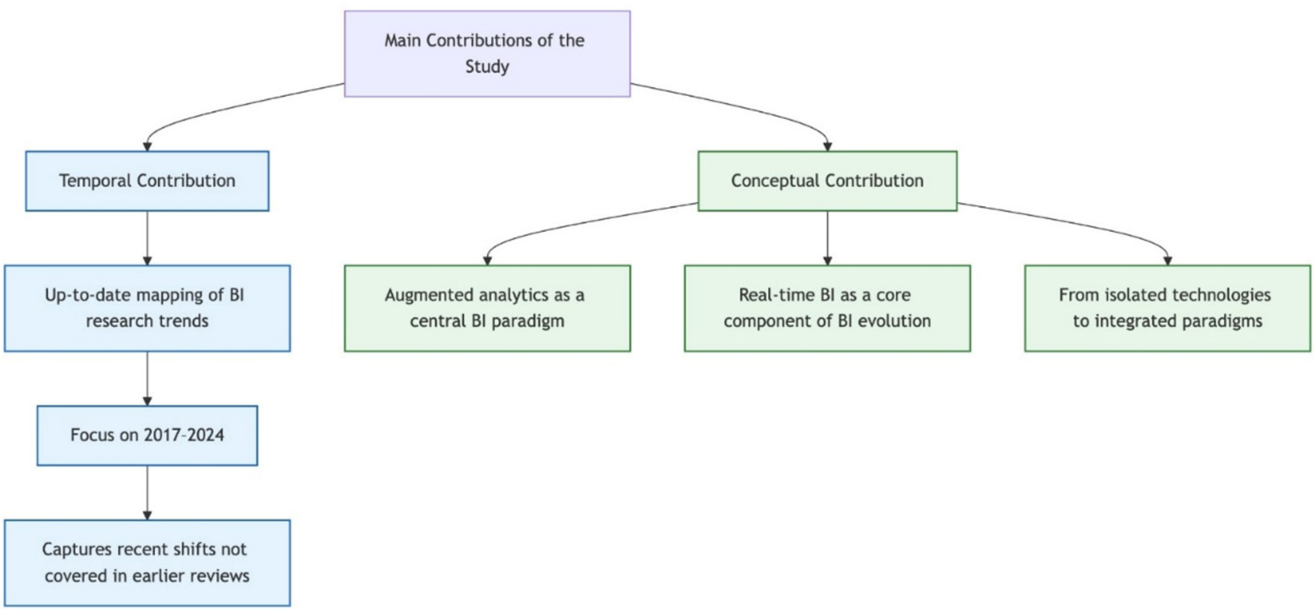

Figure 18. Temporal and conceptual contributions of the study

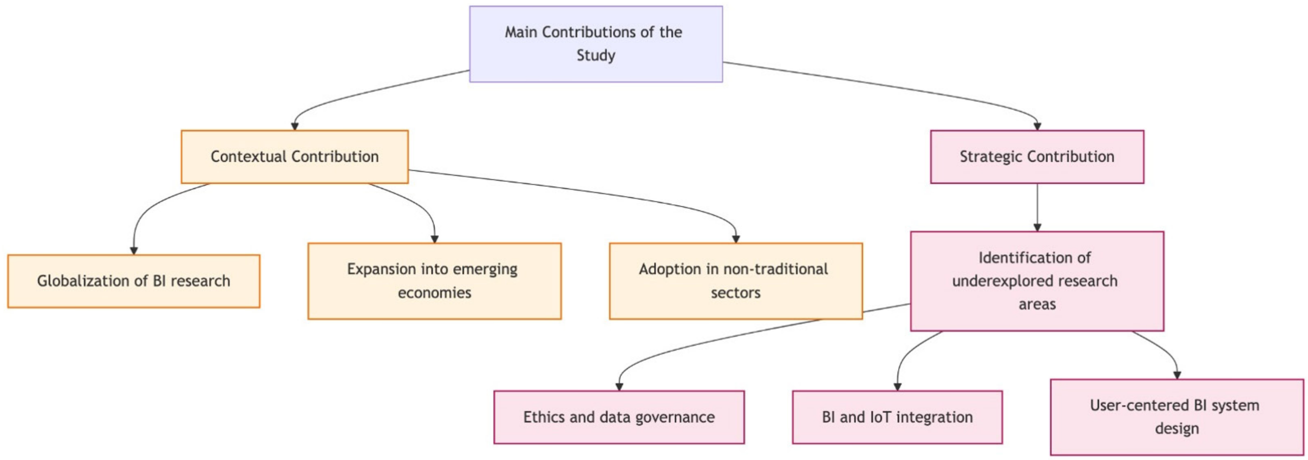

Figure 19. Contextual and strategic contributions and research agenda

Conclusions

This systematic mapping study provides a comprehensive and up-to-date synthesis of research on BI published between 2017 and 2024, offering a structured view of dominant trends, application sectors, geographic distribution, and research gaps. While technologies such as big data and AI continue to dominate the BI landscape, the results demonstrate that BI is undergoing a clear transformation towards more automated, real-time, and cloud-based analytical paradigms.

One of the main contributions of this study is the identification of real-time analytics, cloud-based BI, and augmented analytics as central drivers of current BI evolution. Unlike previous reviews that focused primarily on historical trends or isolated technologies, this work shows how these paradigms collectively enable a shift from descriptive reporting towards predictive and prescriptive decision-making, fundamentally changing how organizations generate value from data. However, the findings also reveal that adoption across industry sectors remains uneven, highlighting the need for more targeted and context-specific empirical studies.

From a sectoral perspective, this mapping confirms that BI adoption is most prominent in social media and digital marketing, healthcare, education, retail, and e-commerce. At the same time, the study identifies emerging domains such as smart energy systems and IoT-enabled environments, indicating that BI is expanding beyond traditional enterprise contexts into cyber-physical and sustainability-oriented ecosystems. This sectoral synthesis represents a concrete contribution since it clarifies where BI is currently consolidated and where it is still evolving.

In terms of geographic distribution, the analysis shows that BI research is globally distributed, with strong research hubs in Asia, Europe, and the Americas, alongside growing contributions from emerging economies. This finding reinforces the notion that BI research is no longer geographically concentrated but rather reflects a progressive globalization of data-driven decision-making practices.

A particularly relevant contribution of this study lies in the explicit identification of underexplored research areas. The results reveal a limited number of studies addressing BI integration with IoT, advanced social network analytics, data ethics, and user-centered BI system design. Additionally, the literature shows a strong bias towards large organizations, with small and medium-sized enterprises (SMEs) remaining largely underrepresented. By systematically highlighting these gaps, this work goes beyond descriptive analysis and provides a clear agenda for future research. Furthermore, considering that the mapping identifies data ethics and governance as underexplored areas, the findings suggest that the technical evolution of BI, particularly driven by AI and ML, is progressing at a significantly faster pace than the development of ethical and regulatory frameworks. This imbalance is generating a growing *governance gap* that may expose organizations to risks related to transparency, accountability, bias, and responsible data use, thereby positioning ethical governance as a critical priority for future research.

In summary, the main contribution of this systematic mapping is not only the identification of current BI trends, but also the integrated interpretation of how BI is evolving technologically, sectorally, and geographically. It also sheds light on the aspects where critical research gaps persist. This study offers researchers a consolidated framework to position future investigations and provides practitioners with evidence-based insights into the strategic directions of BI. Ultimately, the findings reinforce the view of BI as an increasingly comprehensive, automated, and ethically responsible platform that supports agile, data-driven decision-making in complex and competitive environments while underscoring the urgent need to align technological innovation with robust ethical and governance mechanisms in order to ensure a sustainable and trustworthy BI adoption.

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DOI: https://doi.org/10.14483/22487638.23557

REVISIÓN

Sustainable Supply Chain Management in the Context of Small and Medium-Sized Enterprises: A Literature Review and Bibliometric Analysis

Gestión sostenible de la cadena de suministro en el contexto de las pequeñas y medianas empresas: revisión bibliográfica y análisis bibliométrico

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Fecha de Recepción: 24 de abril de 2025 **Fecha de Aceptación:** 15 de diciembre de 2025

Cómo citar: Niño Villamziar., Y.A., Patiño-Castro., O.A., Parra-Peña. J. (2025). Sustainable supply chain management in the context of small and medium-sized enterprises: a literature review and bibliometric analysis. *Tecnura*, 29(86), 129–152. https://doi.org/10.14483/22487638.23557

Abstract

Context: Organizations must strategically address sustainability pressures. In this sense, it is considered that their responses tend to be more effective when adopted at the supply chain level. This approach is framed within the topic of sustainable supply chain management (SSCM), which integrates the environmental and social objectives inherent to sustainability.

Objective: To determine the current status of SSCM in small and medium-sized enterprises (SMEs), given its importance to sustainability and the economy

Methodology: This work uses bibliometric analysis and the Tree of Science, which allows identifying topics, authors, and outstanding journals, as well as the seminal works and the perspectives of development in this area.

Results: The results suggest that it has become a topic of growing interest for the academic community, mainly in Asian countries. Likewise, the considered articles are published in highly recognized journals, and the most cited topics refer to the environmental dimension.

Conclusions: Delving into the particularities of SSCM in SMEs contributes to the academic debate to support the path towards sustainability in this type of organization, which face their own challenges, given their characteristics, resources, and capabilities.

***Keywords*:** sustainable supply chain management, small and medium-sized enterprise, sustainability, literature review, bibliometrics, Tree of Science

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Resumen

Contexto: Las organizaciones deben abordar estratégicamente las presiones de la sostenibilidad. En este sentido, se considera que sus respuestas tienden a ser más efectivas cuando se adoptan a nivel de la cadena de suministro. Este enfoque se enmarca en la gestión sostenible de la cadena de suministro (SSCM), que integra los objetivos ambientales y sociales inherentes a la sostenibilidad.

Objetivo: Determinar el estado actual del área de SSCM en las pequeñas y medianas empresas (PyMEs), dada su importancia para la sostenibilidad y la economía.

Métodología: Este trabajo utiliza el análisis bibliométrico y Tree of Science, que permite identificar los temas, autores y revistas destacados, así como los trabajos seminales y las perspectivas de desarrollo de esta área.

Resultados: Los resultados sugieren que este se ha convertido en un tema de creciente interés para la comunidad académica, principalmente en los países asiáticos. Asimismo, los artículos considerados se publican en revistas de gran reconocimiento, y los temas más citados se refieren a la dimensión ambiental.

Conclusiones: Profundizar en las particularidades de SSCM en las PyMEs contribuye al debate académico para apoyar el camino hacia la sostenibilidad de este tipo de organizaciones, ya que ellas afrontan sus propios retos, dados sus características, recursos y capacidades.

***Palabras clave*:** gestión sostenible de la cadena de suministro, pequeña y mediana empresa, sostenibilidad, revisión bibliográfica, bibliometría, Tree of Science

Introduction

Sustainable development is one of the main drivers that have shaped the late 20th century [1] at its political foundations since the publication of the Brundtland report in 1987. In conceptual terms, one stream of literature highlights that and have been used interchangeably in many cases, and that, although they are deeply related, they are distinct [2], [3]. However, there seems to be consensus on the fact that, in both cases, they include environmental, economic, and social dimensions, between which there are deep tensions and complexities [4].

In the business sector, has been defined in several ways [5]. One of them considers actions aimed at minimizing the negative impacts of a business on people, society, and the environment while maintaining or enhancing value for customers and other stakeholders [6]. Broadly, it involves the resilience of organizations over time when they are closely connected to healthy environmental, economic, and social systems, placing them in a better position to respond to internal and external shocks [5].

These corporate sustainability concerns have been extended to the field of supply chain management (SCM), which is attracting the attention of the academic and business world [6], mainly under the knowledge domains of green supply chain management (GSCM) and sustainable supply chain management (SSCM). For many authors, SSCM constitutes a broader approach than GSCM by integrating social aspects with economic and environmental ones in a triple-bottom-line view [5], [7].

In the field of SSCM, the existence and contributions of previous research stand out: there are those offering conceptual frameworks [5], [8], those employing bibliometrics as their main methodology [9]–[12], and those focusing on the specific context of developing countries [13], among others. Despite the number and importance of said contributions, review works focused on small and medium-sized enterprises (SMEs) are still limited [14], even though the impact of these organizations on sustainable development has been recognized, as well as the need for specific solutions to improve sustainability performance, given the differential characteristics of these entities [15].

Thus, research should pay more attention to SMEs, not only because of their importance for achieving sustainable outcomes, but also because their aggregate impacts are likely to be considerable [13]. According to the Organization for Economic Co-operation and Development (OECD), SMEs are the predominant form of enterprise, representing 99% of the total [14].

In light of the above, the main purpose of this document is to map the scientific literature published on the topic of SSCM in SMEs. Specifically, the questions that guide the review are the following:

- What are the main thematic axes?
- Which are the authors, journals, institutions, and countries with the most contributions?
- Who are the seminal authors and who represents the current perspectives?
- Who are the authors with the highest number of contributions?

The following paragraphs highlight the theoretical elements of sustainability and its relation to the management of organizations and supply chains, especially in the context of SMEs.

Sustainability and sustainable development

In academic terms, it stands out that, since the late 1990s, there has been a considerable increase in the number of publications related to sustainability [7]. Despite this, some authors, such as [16], consider that it is still necessary to clarify the concept and use of the terms *sustainability* and *sustainable development*, which have been erroneously used as synonyms [2], [3].

One of the proposals for this conceptual difference was established by [2], who emphasized that sustainability ensures, in the long term, that our planet can meet the material and energy needs to sustain complex systems—including humanity—and that this has economic implications, derived from the consumption of resources, and social implications, since the ultimate goal is to meet society's needs. Sustainable development, on the other hand, provides a vision of how society should be developed in harmony with the environment and adds a greater focus on social dimensions such as intergenerational equity [2].

At the political level, the sustainable development framework was popularized in the 1980s with the most cited definition in the literature, which was given in the Brundtland Report of the World Commission on Environment and Development [1], [17], [18]: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (p.37) [19]. This commission is recognized for opening a discussion—in a detailed, documented, and meaningful way—on social and environmental issues, as well as on the risks faced by humanity [20]. In recent years, the most relevant sociopolitical event occurred in September 2015, when UN member countries agreed on a universal agenda for sustainable development, which consists of 17 goals and 169 associated targets.

This political context is important but needs to be operationalized for companies [21]. In this sense, while social actors have defined the agenda, companies must implement it, as they represent the productive resources of the economy [22]. This has shaped the notion of *corporate sustainability* (CS) [4], which emphasizes the interactions between economic, environmental and social values [23]. Currently, the debate is focused on the concept and its implications in the business context. While there is no consensus on a definition of CS, it is recognized that "corporate growth and profitability are important, [but] it also requires that the corporation pursue social goals, specifically those related to sustainable development-environmental protection, social justice and equity, and economic development" [4].

According to [5], the definitions of CS and *corporate social responsibility*, which cannot be used as synonyms for one stream of literature, share many aspects in common: they focus on an integrated view of the triple bottom line, address the needs of key stakeholders, assume a long-term perspective, and start from the need to build resilient organizations. Many of their related initiatives are voluntary.

SC performance has moved from a perspective based on individual company actions to the link with SCM [24]. Thus, organizations know that all aspects of SCM are more important than ever and pay strategic attention to them [25]. With these aspects in mind, the next subsection provides a framework for sustainable SCM.

Sustainable supply chain management

This awareness has given rise to the knowledge domain of GSCM, defined as integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life [26, p. 54-55].

As stated in the literature, GSCM mainly focuses on economic and environmental dimensions. Thus, the consideration of social aspects is included in the concept of SSCM, which represents a progression of GSCM and a dominant research domain since 2010 [7]. Although there are several definitions of SSCM, the most commonly cited [5] are as follows:

as the management of material, in-formation and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements. [8, p. 1700] as the strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key interorganizational business processes for improving the long-term economic performance of the individual company and its supply chains. [17, p. 368]

There are at least two positions in the literature. In the first, the boundaries between SSCM and GSCM are still nuclear [5], [27]. In the second, SSCM is an evolution of GSCM that integrates environmental, economic, and social dimensions in SCM [7].

Sustainable supply chain management in SMEs

The study of sustainability in the supply chain has focused mainly on large companies, which are generally subject to greater pressure from stakeholders, demanding that they make their products and operations environmentally sustainable [28]. In the case of SMEs, academic research is still in development, and more studies, analyses, and discussions are required to develop the theoretical framework of GSCM [29].

According to [30], firm size influences the decision to allocate resources and capabilities for the implementation of GSCM. In the case of SMEs, the findings are not generalizable; some have found that, due to their various limitations, it is too difficult to effectively adopt GSCM strategies [29], and others suggest that, compared to large companies, SMEs have greater flexibility and ease in achieving social and environmental objectives, and that this requires the development of strategies which are appropriate to their characteristics.

According to [28], in a SCM framework, SMEs have limited human and financial resources for activities including supplier development and certification, as well as reduced bargaining power in negotiations with their suppliers. In addition, they face fewer pressures for environmental awareness. On the other hand, the adoption of GSCM practices by smaller companies can leverage the knowledge and resources of their large supply chain partners.

Within the current framework, and to achieve the purposes of our literature review, this document is organized into the following sections: the methodology for gathering, organizing, and analyzing the information, including search criteria and document selection; the findings; and the conclusions of the review.

Methodology

As shown in Fig. 1, the methodology for our literature review followed two stages: (i) the search and selection of documents, and (ii) the analysis of the information using the Tree of Science and bibliometrics.

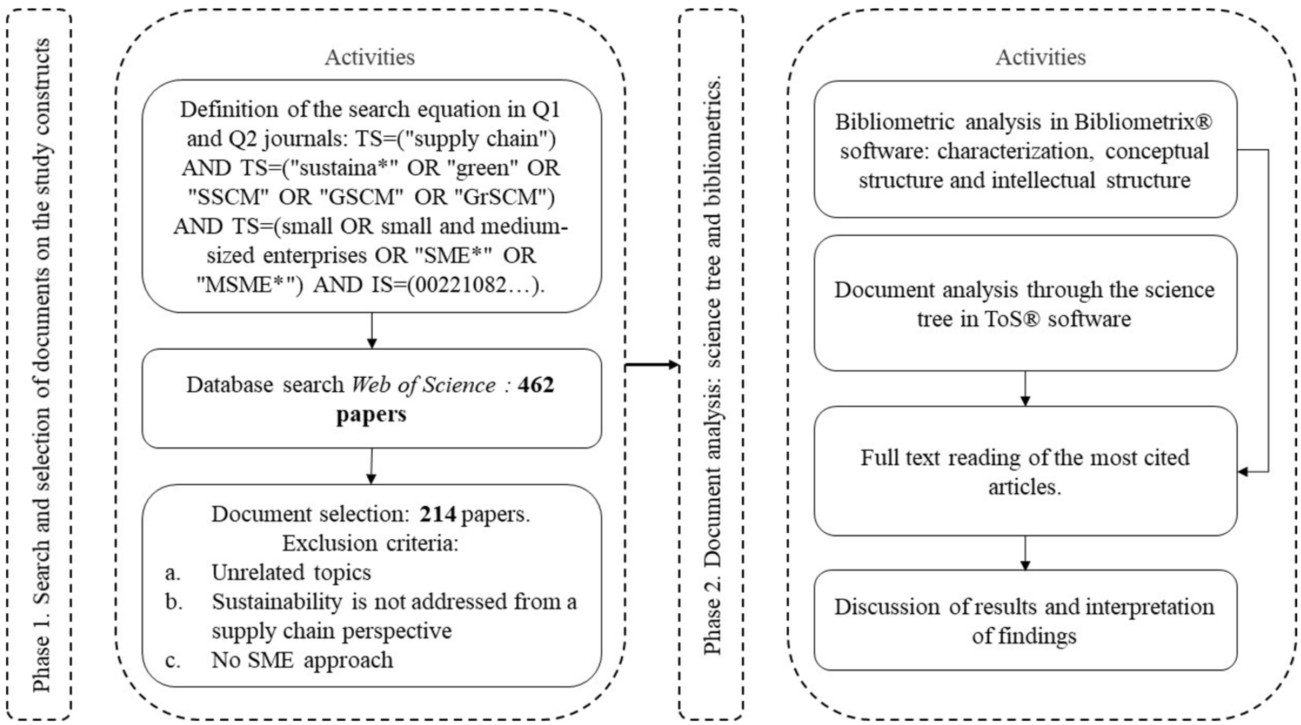

Figure 1. Methodology for literature review

Search and selection of documents

The first stage was the document search, which was conducted in the Web of Science (WoS) database, considering journals ranked Q1 and Q2 in the area of *Business, Management and Accounting* (Scimago), for a total of 823 journals as of 2023. The WoS database was selected for two reasons. The first is that, like Scopus, it provides current and relevant information in multidisciplinary fields [31]. The second is its quality standards regarding the metadata required for bibliometric analysis [32].

The search keywords were established based on the specific topic and context of the research: "sustainable supply chain management" and "small and medium-sized enterprises (SMEs)." These words, together with Boolean operators and symbols, allowed for the refined construction of the following search equation:

TS=("supply chain") AND TS=("sustaina*" OR "green" OR "SSCM" OR "GSCM" OR "GrSCM") AND TS=(small OR small and medium-sized enterprises OR "SME*" OR "MSME*") AND IS=(00221082…).

Under this search equation, we obtained 462 articles (including early-access and review articles) published in English between 2004 and 2023. We subjected them to a detailed relevance analysis based on their titles, keywords, and abstracts. Articles were excluded (i) if the sustainability aspects of SMEs were not addressed from a SCM perspective and (ii) if they bore no relation the topic (SSCM) or the unit of study (SMEs).

It is also important to point out that, when the keywords assigned by the journals (keywords plus) but not by the authors contributed to some of the constructs of interest of the study, the articles were fully reviewed in order to decide on their inclusion. Thus, before the bibliometric analysis, 221 articles were fully read, out of which 19 met the inclusion criteria. This stage can be regarded as a contribution to the bibliometric methodology since it minimizes the risk of including documents that do not correspond to the area or purpose of the research. As a result of this filter, 214 documents were obtained for subsequent analysis.

Document analysis

The 214 documents were subjected to an initial analysis based on bibliometrics, which is defined as an interdisciplinary science with the purpose of studying written scientific communication through indicators, methods, and statistical and mathematical models, using information obtained from academic databases [33]. In the management area, this type of analysis has proven useful for providing retrospective insights in different fields of business research [34].

For this analysis, the Bibliometrix 4.0 software was used since it is an open-source tool for conducting complete scientific mapping analyses of the academic literature [35]. We followed the structure presented in Tabla I [32].

Table I. Structure of our bibliometric analysis

Domain focus	**K structures**
Level of analysis	Structures[a]
Metrics	Bibliometric technique
	Unit of analysis
Summary	Statistical technique
Key information	
Annual scientific production	Conceptual
	Co-Words
Sources	Author keywords
Highlighted by impact metrics (H index)	Thematic map
Authors	Intellectual
	Co-citation[b]
Countries	Citation
Outstanding by impact metrics (H index)	Articles
Scientific production by country	Authors
	Sources
Cited papers and references	Network analysis
Most cited papers	
Word cloud	

a. Bibliometrix also includes a social structure. Given the purpose of this work, is not included in the results.
b. For some, this is the most important analysis since it constitutes the most abundant source of data

These results were complemented using the Tree of Science (ToS). ToS is a methodology whose purpose is to reduce the search for fundamental articles in an area of knowledge, based on the analysis of citation networks, in order to identify authors and outstanding articles in a field via algorithms based on graph theory [36].

Results

For the initial analysis of the literature, a bibliometric approach was used, based on maps that represent the connections within the research field [37]. These were constructed using Bibliometrix to identify research approaches, representative authors, and the terms that most influence the knowledge domain under study [38].

General characterization of the publications

The bibliometric analysis was performed with 214 documents involving 629 authors. The observation window spanned between the years 2004 and 2023, considering that previous reviews state that SSCM research has received increasing attention in the last decade [13]. Fig. 2 shows the number of publications per year, exhibiting an average annual growth rate of 19.81%. Moreover, starting in 2017 and up to the end date of the observation window, there is growing interest in SSCM research in SMEs.

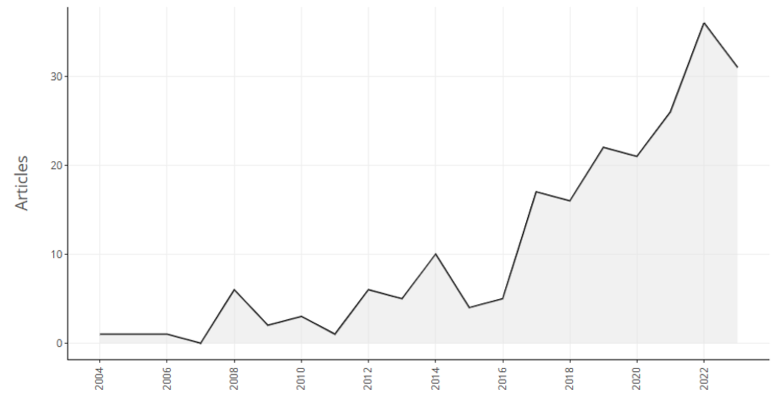

Figure 2. Annual scientific production in the area of SSCM in SMEs

Concerning the number of publications by country, India, China, United Kingdom, Italy, Indonesia, and Brazil are in the first six places, as shown in Figura 3, where the label *SCP* (single country publication) corresponds to intra-country publications and MCP (multiple country publication) refer to inter-country research works. Colombia ranks 19th with three publications by Professor Van Hoof from Universidad de Los Andes.

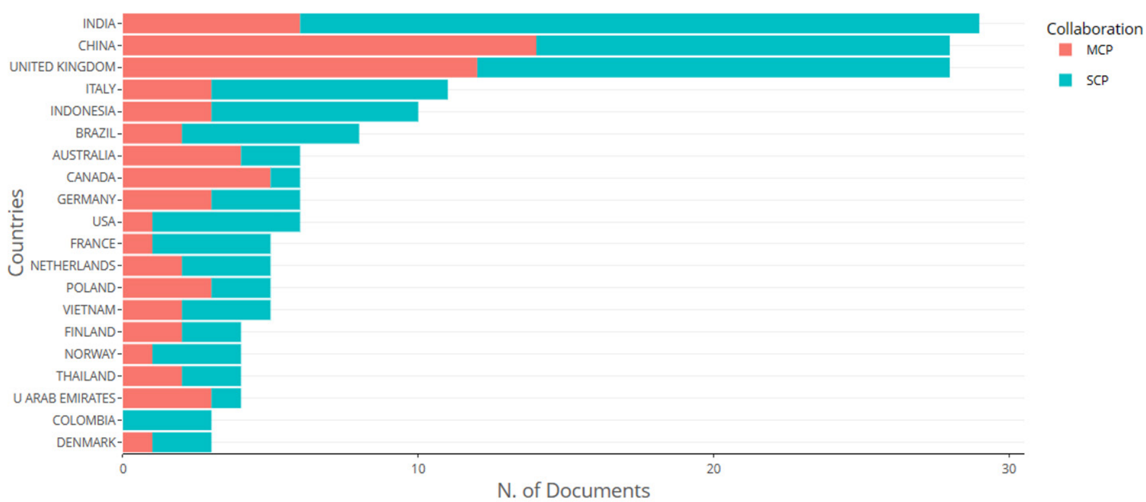

Figure 3. Scientific production by country

This result is in line with the findings of other studies, which indicates a gap in SSCM and the lack of research of non-Western and non-Asian origin [13].

Leading journals in the field

The analyzed articles were published in 64 journals ranked in quartiles 1 and 2 according to their impact factor, which can be regarded as evidence of scholarly interest in the field. Tabla II lists the 15 journals with the highest number of publications, highlighting the authors' preference for publishing in the *Journal of Cleaner Production*.

Table II. Main journals in the field

Journal	No. of documents	h_index	g_index	m_index	Quartiles
Journal of Cleaner Production	66	31	62	1.55	Q1
Business Strategy and the Environment	13	9	12	0.6	Q1
Journal of Manufacturing Technology Management	10	9	9	1	Q1
Benchmarking: An International Journal	9	4	9	0.667	Q1
Corporate Social Responsibility and Environmental Management	9	7	8	0.438	Q1
Production Planning & Control	9	8	9	0.8	Q1
Supply Chain Management: An International Journal	6	6	6	0.333	Q1
International Journal of Logistics Management	5	3	4	0.429	Q1
International Journal of Emerging Markets	4	1	2	0.500	Q2
Journal of Industrial Engineering and Management	4	3	4	0.75	Q2
Operations Management Research	4	2	3	0.25	Q2
Clean Technologies and Environmental Policy	3	3	3	0.214	Q1
International Journal of Logistics-Research and Applications	3	3	3	0.429	Q1
International Journal of Operations & Production Management	3	1	2	0.143	Q1
International Journal of Production Research	3	1	2	0.111	Q1

Leading articles in the field

Based on the results obtained, Fig. 4 lists the 20 papers with the highest number of citations at the global level, which can therefore be considered relevant for the SSCM domain in SMEs. Within this group, Table III details the purposes, methods, and main results of nine articles, corresponding to the five most cited and the four with the most recent publication dates.

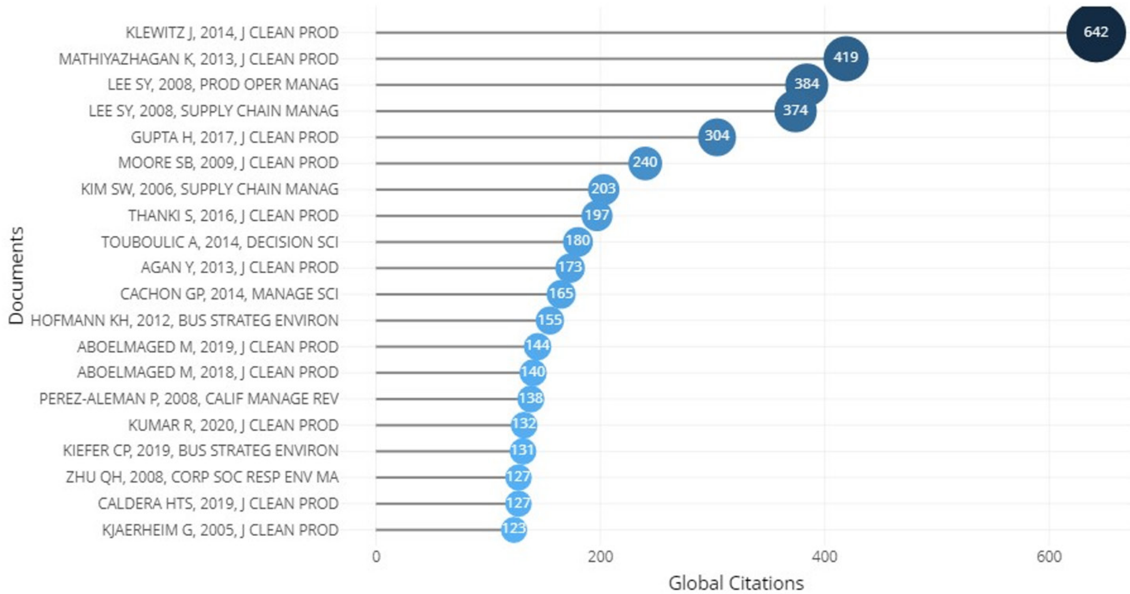

Figure 4. Featured articles in the field

Table III. Most cited articles in the SSCM domain for SMEs

Reference	Purpose	Method	Main findings
[39]	To analyze research between 1987 and 2010 on innovation practices, including different types of sustainability-oriented innovations and strategic sustainability behaviors of SMEs.	Systematic literature review.	The authors highlight three aspects: (i) the strategic sustainability behavior of SMEs ranges between resilient, reactive, anticipatory, innovation-based, and rooted in sustainability; (ii) innovation practices are identified at the product, process, and organizational levels; (iii) research continues to focus on eco-innovation rather than innovation from a triple-bottom-line perspective.
[40]	To identify the dominant barrier to GSCM adoption in the industry.	Qualitative. Interpretive Structural Model (ISM).	Different Indian automotive component manufacturing industries have distinct barriers to GSCM application. However, in its application, especially for maintaining environmental awareness, the dominant barrier is that of the supplier.
[41]	To build a map of the factors that allowed initiating and improving the environmental capabilities of SMEs over time.	Qualitative. Case studies.	This work provides a conceptual framework for understanding and defining the dynamics of environmental capability development for SME suppliers, operationalized into five factors, both internal and external: product, process, organization, supply chain, and external relationships.
[42]	To describe what facilitates small and medium-sized suppliers to engage in supply chain greening initiatives.	Quantitative. Sample 142 SMEs in South Korea.	This study finds that the willingness of SMEs to participate in GSCM initiatives is largely dependent on two factors: the environmental requirements and support of buyers and the willingness of the supplier. Governments can play an important role in motivating these suppliers. Finally, the paper reveals that the fewer resources and organizational capabilities suppliers have, the more willing they are to participate in such initiatives.

Reference	Purpose	Method	Main findings
[43]	To present a framework for selecting suppliers among SMEs based on their capacity for eco-innovation.	Qualitative. BWM and Fuzzy TOPSIS.	This study presents a framework to help managers select green and innovative suppliers among various SMEs.
[44]	To examine the effect of absorptive capacity on the adoption of green innovations.	Quantitative. Sample: 193 SMEs in an emerging economy.	Absorptive capacity is a strong predictor of sustainable capabilities and green innovation adoption. In addition, sustainable orientation and collaborative capabilities are evidenced as significant determinants of green innovation adoption and mediators of the effect of absorptive capacity on green innovation adoption. Sustainable human capital does not show a significant impact on green innovation adoption.
[45]	To analyze the role of dynamic resources, competencies, and capabilities (RCC) as determinants (drivers and barriers) of different types of eco-innovation (EI).	Quantitative. Sample: 197 Spanish industrial SMEs developing EI.	The results suggest that physical CCRs, participation in green supply chains, and an adequate corporate culture, promote IE; technological drive, market pressure, and internal financial resources represent drivers of these IEs, while cooperation, organizational learning, an ISO green certification, and technological path dependence, constitute barriers.
[46]	To explore the co-evolution of *lean* and *green thinking* and the potential of these practices to enable successful transitions to sustainable business practices.	Qualitative.	Through the adoption of lean and green thinking in the transition to sustainable business practices, SMEs can contribute more quickly to the circular economy at the enterprise level.
[47]	To investigate the challenges of applying Industry 4.0 technologies in SMEs for ethical and sustainable operations.	Qualitative. DEMATEL.	The challenges have been categorized as cause and effect. In the causes, the main challenge is the lack of motivation of partners and customers in the application of I4.0 technologies. In the group of effects, the fear of failure of I4.0 technologies stands out.

Source: Authors

When reviewing these papers, a very concrete focus on the environmental perspective of sustainability is evident, which is in line with previous findings, wherein the need to delve deeper into the social dimension of SSCM is established as a research gap [13], [48]. Furthermore, in the context of SMEs, the idea that entrepreneurial orientation through the components of innovation, proactivity, and risk-taking can lead to a greater commitment to sustainability has received empirical support in several works [15]. This is reflected in the perspective of the most cited articles, in which eco-innovation or ecological or green innovation are highlighted within the thematic axes.

Structures of the publications

Conceptual structure

The analysis of thematic networks was based on the keywords defined by the authors of the papers. As a result, the network shown in Fig. 5 is presented below. Similarity was calculated while considering the co-occurrence of the keywords identified in the set of publications. The authors' keywords were considered since they express the orientation and descriptors through which they present their work to the scientific community. The node size reflects the frequency (weight) of occurrence of the words. Sustainability, SMEs, SCM, and circular economy are highlighted as those with the highest level of importance, which is reinforced in Fig. 6.

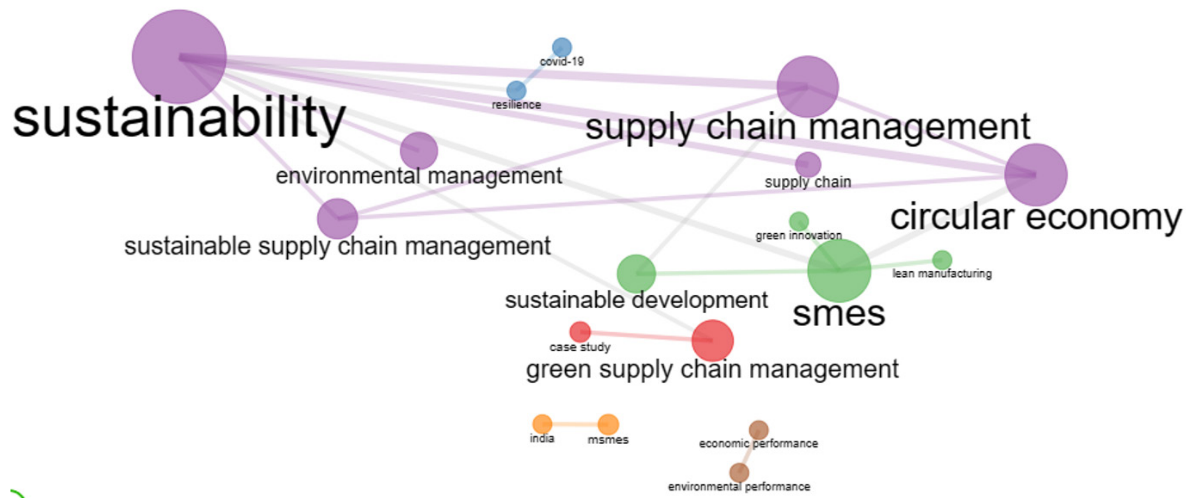

Figure 5. Keywords of the authors

Figure 6. Cloud of main author keywords

As expected, the terms that stand out for their frequency are those that integrate the search equation, so the analysis focuses on other words relevant to the authors of the analyzed documents. Based on this, it is possible to establish the conceptual link between SSCM and the domains of circular economy and corporate responsibility, which can be also considered for analyzing the case of developing countries. Other terms relate to innovation, barriers, and the inclusion of microenterprises as objects of study.

Intellectual structure

Co-citation represents the frequency with which two units of analysis are cited by other documents, under the assumption that the more two items are cited together, the more likely it is that their content is related [49]. In the case of co-cited authors, four clusters of authors were observed (Fig. 7). The red cluster includes authors who have specifically addressed SSCM, highlighting Seuring and Carter as widely cited. In the green cluster are the authors who have developed the topic of SSCM more strongly, *e.g.*, the works of Zhu and Sarkis, recognized as pioneers in the topic of practices; or that of Srivastava, who is credited with the most cited definition in this field. The blue cluster points to the methodological approach of structural equations and a theoretical approach to the natural resource-based view of the firm, proposed by Hart in 1995. Finally, the purple cluster includes authors who have addressed issues in this domain of knowledge under the theoretical lens of Barney in 1991, *i.e.*, based on the theory of resources and capabilities.

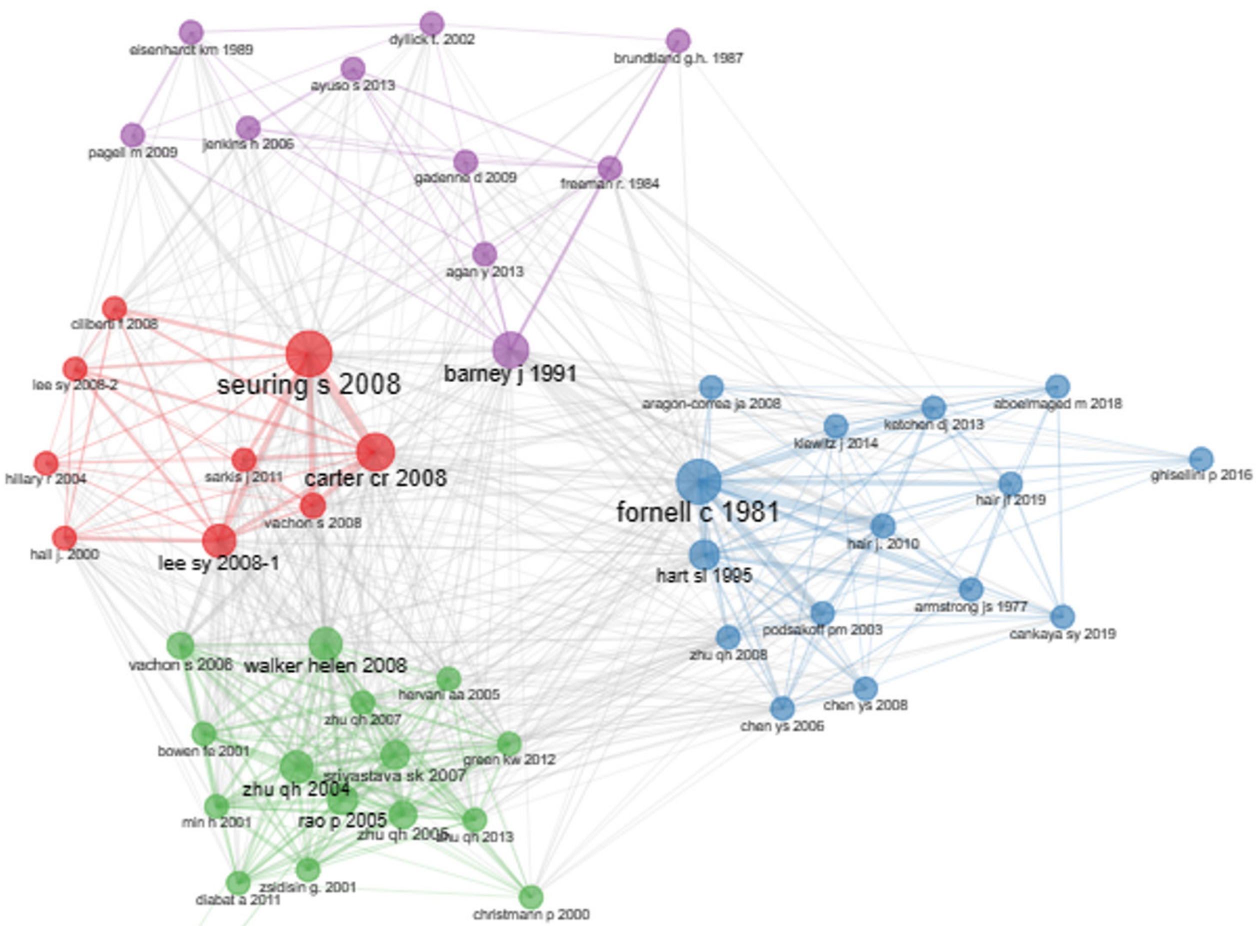

Figure 7. epresentative authors in the field

Tree of Science

The ToS methodology produced 90 documents, with 20 articles in the root, 20 in the trunk, and 50 in the leaves or branches (details can be found in Appendix 1). The articles found at the root correspond to research that supports the theory of the area of knowledge under review [50]. For this case, 20 articles in three streams were identified. The first is specific to the subject area, with outstanding authors such as Seuring, Zhu, Carter, Vachon, Srivastava, and Sarkis. The second focuses on methodological aspects and makes extensive use of the structural equations method, *e.g.*, the papers by Fornell and Hair. Finally, the third deals with the theories that have supported the area, with the works of Barney and Hart.

20 articles are contained in the trunk, which, according to the ToS, are those that begin to shape the theory, are more specific on the subject, and have become benchmarks over time [36]. The keywords associated with the trunk are impact, performance, drivers, environmental management, and management, which are in turn associated with drivers, practices, and performance results. These are the main constructs that make up the conceptual frameworks of GSCM/SSCM [9], [30], [51]–[53].

The different perspectives under which the subject has been developed are located in the branches [36]. They amount to 51 works, under the following keywords: performance, impact, framework, management, and innovation. In general, with the ToS tool, it is possible to establish the seminal works (root) and the thematic perspectives in this area of research based on the articles in the trunk and branches.

Conclusion

From the questions that guided this literature review, the first finding that should be highlighted in the area of SSCM for SMEs is the increase in the number of publications, mainly since 2016, in response to a call from the academic community to pay more attention to this type of companies, given their role in improving environmental management and performance in the broader competitive framework of the supply chain [41]. The increasing attention of this knowledge domain has been established in different literature reviews, concluding that it is likely to increase in the coming years because of an increased awareness of environmental sustainability around the world [11], [27], [54].

In the area of SSCM/GSCM in general, studies such as that by [54] conclude that they are relatively new disciplines; more than 70 percent of the contributions come from only 15% of the first authors. In addition, significant contributions have come mainly from researchers from China, followed by USA, UK, Taiwan and India. The cited authors consider that this field is still in its early stages and requires significant attention to take the current research to the next level. This behavior differs slightly when the unit of analysis is SMEs, highlighting India, China, and the UK as the countries with the highest number of contributions. However, this study also ratifies the need for research of non-Asian origin [13] and in the context of developing countries [55].

With respect to the journals with the highest number of publications, it is important to highlight two aspects: the first is the interest in publishing the findings of SSCM in SMEs in journals classified in quartiles 1 and 2, which can be considered a sign of their academic importance; the second is the authors' preference for publishing in the *Journal of Cleaner Production*, given its wide recognition in the academic world, which makes it a key reference for researchers.

On key topics and authors, the results regarding the intellectual structure of the bibliometric analysis and the seminal papers of the science tree are in line with other literature reviews, which evidence the dominant influence of the work done by Zhu and Sarkis on GSCM practices and performance [9]. The topics of the most cited articles include eco-innovation, defined as innovations that reduce the environmental impact of consumption and production activities [45], and, in all cases, the environmental dimension of sustainability prevails. Thus, the findings of this review support the call for academics to approach this area from a triple-bottom-line perspective.

As for co-cited authors, the works are divided into four groups. The first group includes authors who have specifically addressed SSCM, with Seuring and Carter standing out as widely cited authors. The second group includes authors who emphasize the environmental dimension of SCM, with Zhu and Sarkis being recognized as pioneers in the subject of practices, and Srivastava as having provided the most cited definition in this field. The third group has a methodological emphasis on structural equations and a theoretical approach to the natural resource-based view of the firm proposed by Hart in 1995. Finally, the last group includes authors who have addressed issues in this domain of knowledge under the lens of resource and capability theory.

In general, the results show the academic importance of SSCM in SMEs, its authors, and tis representative topics, and they corroborate the need to strengthen research in this area, mainly in developing countries of non-Asian origin, to build a body of knowledge on which to design policies appropriate to the characteristics and needs of SMEs.

This article contributes to the literature on SSCM by expanding the body of knowledge in this area within the context of SMEs, marking an initial step towards promoting research for this type of company, which, due to its distinctive characteristics, necessitates specific analysis and solutions. Although several literature reviews have been conducted in the field of SSCM, few focus on SMEs, despite their importance to the economy and sustainability.

As a continuation of this literature review, different research possibilities are suggested. One of them is to document the results achieved by SMEs in each of the constructs that make up the conceptual framework of SSCM, namely drivers, practices, and performance results, in order to establish a holistic view under the triple-bottom-line approach. Another avenue for future research is to delve deeper into the findings of empirical studies conducted on SMEs and explicitly document the theories that have guided them. While it is true that previous reviews have highlighted the use of resource-based view theory [11], [56], another school of thought maintains that SMEs do not possess rare, valuable, and difficult-to-imitate resources that allow them to achieve competitive advantages. Therefore, a practice-based view [57] has emerged as an alternative, which, in the case of SCM, has been dubbed the *supply chain practice view* (SCPV) [58]. With it, it is possible to identify how these types of companies manage to improve their performance within a framework of sustainability.

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Appendix. Tree of science for the SSCM knowledge domain in SMEs.

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CONTENIDO

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Resumen

Debe establecer el objetivo y alcance del trabajo, una descripción clara y concisa de la metodología, los resultados y las conclusiones obtenidas. Máximo 250 palabras.

Palabras clave

Debe escogerse entre tres y diez palabras clave, escritas en español con letra *Times New Roman*, en negrita y cursiva.

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Introducción

Debe describir el planteamiento general del trabajo, así como contexto, antecedentes, estado de arte de la temática abordada, objetivo y posible alcance del trabajo.

Metodología

La redacción de este apartado debe permitir a cualquier profesional especializado en el tema replicar la investigación.

Resultados

Explicación e interpretación de los hallazgos. Si es necesario, se puede presentar una discusión breve y enfocada a la interpretación de los resultados.

Conclusiones

Implicación de los resultados y su relación con el objetivo propuesto.

Financiamiento

Mencionar la investigación asociada de la cual se derivó el artículo y la entidad que avaló y financió dicha investigación.

Agradecimientos

Preferiblemente deben ser breves y deben incluir los aportes esenciales para el desarrollo del trabajo.

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El pie o rótulo de cada figura debe incluir la palabra Figura (en negrita) seguida del número consecutivo correspondiente y de una breve descripción del contenido de la figura. El pie de figura debe estar escrito con letra Times New Roman, en cursiva y tamaño de fuente 9. Las figuras deben ir nombradas y referenciadas en el artículo, en estricto orden. Toda figura debe tener también la fuente de la que fue tomada, o mencionar que es autoría de los autores si es el caso.

Símbolos

Los símbolos de las constantes, variables y funciones en letras latinas o griegas –incluidos en las ecuaciones– deben ir en cursiva; los símbolos matemáticos y los números no van en cursiva. Se deben identificar los símbolos inmediatamente después de la ecuación. Se deben utilizar las unidades, dimensiones y símbolos del sistema internacional.

Cuando se empleen siglas o abreviaturas, se debe anotar primero la equivalencia completa, seguida de la sigla o abreviatura correspondiente entre paréntesis y en lo subsecuente se escribe solo la sigla o abreviatura respectiva.

Referencias bibliográficas

Todas las referencias bibliográficas citadas dentro del texto se encuentran listadas en la sección Referencias. El formato en que se cita es el establecido por el Institute of Electrical and Electronics Engineers (IEEE). Puede consultar los materiales que pone a disposición el sistema de bibliotecas de la Universidad Distrital Francisco José de Caldas o el documento oficial de la IEEE

ENVÍO DE ARTÍCULOS

Los autores deben enviar sus artículos a través de la aplicación para tal fin del Open Journal System en formato digital, adjuntando la carta de presentación y el formato de información artículo-autores.

Carta de presentación

El artículo debe ir acompañado de una carta de presentación dirigida al director y editor de la revista, Ing. Lely Adriana Luengas Contreras, donde incluya:

- Solicitud expresa de considerar su artículo para publicarlo en la revista Tecnura.

- Título completo del trabajo.
- Nombres completos de todos los autores del trabajo.
- Certificación de la originalidad y el carácter inédito del trabajo.
- Exclusividad de su remisión a la revista Tecnura.
- Confirmación de la autoría con la firma de todos los autores.

Esta carta deberá estar firmada por todos los autores, escanearse y enviarse junto con los demás documentos solicitados.

Formato de información artículo-autores

El artículo además debe ir acompañado de un formato de información sobre el artículo y sus autores, el cual se puede descargar de la página web de la revista Tecnura: http://revistas.udistrital.edu.co/ojs/index.php/Tecnura, en la sección "Formatos y Documentos". Es importante completar todos los campos de información solicitados, algunos de ellos tienen comentarios para aclarar mejor lo que se está solicitando. El formato no debe escanearse.

Artículo

Artículo en formato digital (Word 2003 en adelante) que cumpla con todas las normas de presentación descritas en el capítulo 3, "Formato del artículo", de la presente en las instrucciones a los autores.

PROCEDIMIENTO PARA LA PUBLICACIÓN

El procedimiento que sigue la revista Tecnura para la evaluación y posible publicación de los trabajos enviados por los autores es el siguiente en orden cronológico:

1. Envío del articulo acompañado de la carta de presentación y el formato de información por parte de los autores.
2. Notificación al autor de correspondencia de la recepción del artículo.
3. Verificación del tema del artículo con respecto a las áreas de interés de la revista.
4. Verificación de las normas de presentación por parte del monitor de la revista.
5. Notificación al autor de correspondencia de la evaluación de las normas de presentación.
6. Envío de las correcciones realizadas por los autores con respecto a la evaluación de las normas de presentación

7. Envío del artículo a los árbitros seleccionados.
8. Notificación del inicio del proceso de arbitraje del artículo.
9. Notificación a los autores de la decisión tomada por el Comité Editorial y de las evaluaciones hechas por los árbitros.
10. Envío de las correcciones realizadas por los autores con respecto a las evaluaciones de los árbitros.
11. Estudio de la versión final del artículo y de las evaluaciones de los árbitros por parte del Comité Editorial.
12. Envío por parte de los autores de la carta de cesión de derechos al editor de la revista.
13. Envío de la versión con corrección de estilo y diagramada a los autores.
14. Verificación de errores y aprobación final de la versión con corrección de estilo y diagramada por parte de los autores.
15. Publicación del artículo en el número correspondiente de la revista Tecnura.
16. Notificación a los autores de la publicación del número de interés.
17. Envío de un ejemplar de la revista a cada autor del artículo publicado.

PROCESO DE ARBITRAJE DE ARTÍCULOS

Considerando la periodicidad trimestral de la revista, el Comité Editorial realiza cuatro convocatorias anuales para la recepción de artículos, aproximadamente en los meses de febrero, mayo, agosto y noviembre. Los artículos serán recibidos hasta la fecha máxima establecida en cada convocatoria.

Una vez recibidos los artículos el monitor de la revista realizará una primera evaluación de forma para verificar que cumplan con todos los elementos mencionados en esta guía de instrucciones a los autores. Luego de recibir nuevamente el articulo con las correcciones de forma solicitadas por el monitor de la revista, este será sometido a evaluación por tres pares académicos (paulatinamente se espera incorporar un mayor número de pares externos que participen en el proceso).

Cada artículo remitido a la revista Tecnura es revisado por dos pares académicos externos a la institución de los autores, mediante un proceso de “revisión entre pares” (*Peer-review*) de doble-ciego, garantizando el anonimato de los autores y evaluadores; se considera confidencial todo trabajo recibido y así se le exige a sus evaluadores.

Las posibles conclusiones de los resultados de la evaluación por parte de los árbitros son únicamente tres: publicar el artículo sin modificaciones, publicar el artículo con modificaciones o no publicar el artículo.

Posteriormente, el Comité Editorial toma la decisión de publicar o no los artículos, con base en los resultados de las evaluaciones realizadas por los árbitros asignados. En caso de existir contradicciones en las evaluaciones con respecto a la publicación de un artículo, el Comité Editorial enviará el artículo a un tercer árbitro y se inclinará por las dos evaluaciones que tengan el mismo concepto respecto a la publicación del artículo.

En cada convocatoria el autor de correspondencia debe sugerir al menos cuatro posibles evaluadores externos a su institución laboral, los cuales deben ser especialistas en el tema específico del artículo remitido, tener al menos maestría y por lo menos dos deben ser internacionales. Los posibles evaluadores pueden pertenecer a una universidad o industria, pública o privada; de estos se debe proporcionar el nombre completo, su formación académica más alta, su afiliación institucional y su correo electrónico. Estos cuatro potenciales evaluadores serán analizados por el Comité Editorial a fin de ampliar la base de datos de los árbitros de la revista Tecnura.

El Comité Editorial de la revista Tecnura se reserva los derechos de impresión, reproducción total o parcial del artículo, así como el de aceptarlo o rechazarlo. Igualmente, se reserva el derecho de hacer cualquier modificación editorial que estime conveniente; en tal caso el autor recibirá por escrito recomendaciones de los evaluadores. Si las acepta, deberá entregar el artículo con los ajustes sugeridos dentro de las fechas fijadas por la revista para garantizar su publicación dentro del número programado.

CONTACTO

Para cualquier solicitud de información adicional puede comunicarse a través del correo electrónico de la revista Tecnura: tecnura@udistrital.edu.co, tecnura@gmail.com, o por mensajería con el Ing. Lely Adriana Luengas Contreras, Director y Editor de la revista Tecnura, a la dirección:

Revista Tecnura
Sala de Revistas, Bloque 5, Oficina 305. Facultad Tecnológica
Universidad Distrital Francisco José de Caldas Transversal 70 B N. 73 a 35 sur
Teléfono: 571 – 3239300 Extensión: 5003
Celular: 57–3153614852
Bogotá D.C., Colombia
Email: tecnura.ud@correo.udistrital.edu.co, tecnura@gmail.com
Página web: https://revistas.udistrital.edu.co/ojs/index.php/Tecnura

Instructions for authors

https://revistas.udistrital.edu.co/index.php/Tecnura/about/submissions

CONTENT

- Scope and editorial policy of the journal
- Type of accepted articles
- Article format
- Article submission
- Publication procedure
- Article arbitration
- Contact

Tecnura journal is an institutional publication of the Faculty of Technology from University Francisco José de Caldas. It is a scientific and technological publication with quarterly periodicity, which is published in January, April, July and October. The first issue appeared in the second semester of 1997 and up to now it has maintained its regularity.

The areas of interest of Tecnura journal are focused on all engineering fields such as electronics, telecommunications, electricity, systems, industrial, mechanics, cadastral, civil, environmental, among others. However, it is not restricted to those; it also has room for education and health issues, as long as they are related to engineering. The journal will only publish concerning scientific and technological research, reflection and revision. In consequence, during the initial editorial evaluation, short articles and case reports will be rejected.

Tecnura Journal is addressed for professors, researchers, students and professionals interested in permanent update of their knowledge and follow-up of scientific-technologic processes in the field of engineering. Tecnura Journal has as mission to disseminate results of research projects in the areas of engineering, through the publication of original and unpublished articles, conducted by academics and professionals accredited by public or private national or foreign institutions. Articles submitted to Tecnura journal must be unpublished works written in Spanish or English; nevertheless, preference will be given to articles that show innovative concepts of great interest, related to the objective and scope of the journal.

Tecnura is an academic publication indexed in the Regional Index Scielo Colombia (Colombia) and Redalyc (México); as well as of the following bibliographic databases: INSPEC of the Institution of Engineering and Technology (England), Fuente Académica Premier of EBSCO (United States), CABI (England), Index Copernicus (Poland), Informe Académico of Gale Cengage Learning (México), Periódica from the Universidad Nacional Autónoma de México (México), Oceanet (Spain) and Dialnet from the

Universidad de la Rioja (Spain). It is also part of the following directories: Online Regional Information System for Scientific journals from Latin America, Caribbean, Spain and Portugal Latindex (México), Bibliographic Index Actualidad Iberoamericana (Chile), e-Revistas (Spain) , DOAJ (Sweden) and Ulrich of Proquest (United States).

Tecnura is a journal arbitrated by a revision process among double blind peers. The schedule of the conformation of its scientific and editorial committee is subject to the publication of articles in internationally indexed journals by their members.

District University Francisco José de Caldas, its directors, the editor, the editorial and scientific committee are not responsible for the opinions and the criteria expressed in the content of the articles and they are published under the exclusive responsibility of the authors and do not necessarily reflect the ideas of the editorial committee.

In addition to the printed version, Tecnura journal also has a digital version available in its web page: http://revistas.udistrital.edu.co/ojs/index.php/Tecnura/index

TYPE OF ARTICLES ACCEPTED

According to the classification of the Scientific and Technological Publications National Index (Publindex-Colciencias), Tecnura journal receives nominations of unpublished articles on the following topics:

- **Scientific and technological research articles:** document that presents, in a detailed manner, the original results of research projects. The generally used structure contains four main parts: introduction, methodology, results and conclusions.
- **Reflection articles:** document that presents research results from an analytic, interpretative or critic perspective from the author, dealing with a specific topic and adopting original sources.
- **Review article:** document that results from a research where the results of published or unpublished research on a science or technology field are analyzed, systematized and integrated, in order to state the advances and tendencies in development. It is characterized for presenting a careful bibliographical review of at least 50 references.

ARTICLE FORMAT

About the appropriate language and style for articles writing

- Authors must use simple sentence structures, avoiding those too long or complex.

- The vocabulary used must be basic and common. Technical language must be briefly explained; also, the meaning of the acronyms must be given the first time they appear in the text.
- The authors are responsible for their work to be conducted in a professional and ethic manner.

About the length of articles

The articles should not exceed 25 pages in letter size and double space, with symmetric margins of 3 cm. Only in the case of review articles, these 25 pages do not include references.

About the presentation format

Submitted articles must be unpublished works written in Spanish or English, and must be typed in Microsoft Word (2003 and beyond), complying with the following indications:

- *Times New Roman* letter, 12 point (except it is required for some sections).
- One column, double-spaced.
- All the margins 3 cm.
- Paragraphs should be justified without spaces between consecutives and without cutting words.
- Do not include page breaks or section finals.
- If you want to emphasize words or phrases from the text, do not use bold letters but italic.
- Decimals should be pointed with comma (,) and not with period (.).
- Thousands and millions should be pointed with a fine space.
- Avoid footnotes.
- Arabic nomenclature must be used only until the third level.

About the article structure

The papers must have the following structure and comply with the following requirements:

Composition of an article

All the articles submitted for evaluation and possible publication by the Tecnura Journal must have at least the following components:

- Title in Spanish and English.
- Information about the authors.

- Abstract in Spanish and English.
- Key words in Spanish and English.
- Introduction.
- Conclusions.
- Future work (optional).
- Acknowledgements (optional).
- Bibliographical references.

If the article is related to scientific and technological research must have, in addition to the above, the following components:

- Methodology.
- Results.
- Financing.

Title

The title of the article must be short or divided in title and subtitle, attractive for the potential reader and written in capital letters. It should appear centered between the margins, written in *Times New Roman* letter, in bold, font size 18. The title of the article has to be in Spanish and English separated by double space. Maximum 20 words.

Authors

After the title the complete name(s) of the author(s) must be written, with their basic biographical data: undergraduate degree, graduate degree, occupation or position, institutional affiliation (institution where they work), dependency, city, country and e-mail. The above information must be immediately below the author's name.

Abstract

The scope and purpose of the work must be established giving a clear and concise description of the methodology, results presented and the conclusions obtained. Maximum of 250 words.

Keywords

Between three and ten keywords must be chosen, written in English with *Times New Roman* letter in bold and italic.

Key words must be written in alphabetic order and must be as standard as possible, for which it is suggested the use of international databases according to the area of knowledge. For example, in the area of Electrics and Electronics it is suggested to use the IEEE thesaurus and World Bank thesaurus that can be accessed at the following web pages respectively: http://www.ieee.org/documents/2009Taxonomy_v101.pdf, http://multites.net/mtsql/wb/site/default.asp

Abstract in Spanish

Translation to the Spanish language of the text that appears in the abstract, it must be correct and precise.

Keywords in Spanish

Translation to the English language of the keywords in Spanish, they must be correct and precise.

Keywords must be written in the order of the English version and must be as standard as possible, for which it is suggested the use of international databases according to the area of knowledge. For example, in the area of Electrics and Electronics it is suggested to use the UNESCO thesaurus that can be found at the following web pages: http://databases.unesco.org/thessp

Introduction

The general idea of the work must be described, its context, backgrounds, state of the art of the topic, objectives and possible scope of the work.

Methodology

The writing of this part must allow any specialized professional in the topic to replicate the research.

Results

Explanation and interpretation of the findings. If necessary, a brief discussion focused on the interpretation of the results can be presented.

Conclusions

Implication of the results and their relation to the proposed objective.

Financing

Mention the associated research from which the article was derived and the entity that endorsed and financed the research.

Acknowledgments

They should preferably be brief and include the essential contributions for the development of the paper.

Equations

Equations must appear centered with respect to the main text. They must be referenced with consecutive numbers (written in parenthesis close to the right margin). Equations are cited in the main text employing the word equation, and followed by the number in parenthesis. Equations must be made in an appropriate equation editor and compatible with "InDesign" software, as for example the equation editor of Windows.

Tables

In the case of implementation of tables, it is recommended that these are not inserted as images, considering that in that format they cannot be modified. The title of each table must include the word table (in italic) followed by the corresponding consecutive number and a brief name of the table. The heading must be written in TNR letter, italic and font size 9.

Charts are not presented but tables and they should be automatically raised from the text processor. Tables should be named and referenced in the article, in strict order. Every table must have at the bottom the source from which it was taken, or to mention self-authorship if it is the case.

Figures

All the figures or pictures have to be sent in JPG or PNG format with a minimum resolution of 300 DPI, adapted to gray scale.

The footnote or name of each figure must include the word figure (in italic) followed by the corresponding consecutive number and a brief description of the content of the figure. The footnote of the figure must be written in Times New Roman letter, italic and font size 9. Figures must be named and referenced in the article, in strict order. Every figure must have at the bottom the source from which it was taken, or to mention self-authorship if it is the case.

Symbols

The symbols of the constants, variables and functions in Latin or Greek letters –included in the equations- must be in italic; the mathematical symbols and the numbers do not go in italic. The symbols must be identified immediately after the equation. Units, dimensions and symbols of the international system must be used.

When using acronyms or abbreviations, the complete equivalence should be written first, followed by the corresponding acronym or abbreviation in parenthesis and from there it is only written the respective acronym or abbreviation.

Bibliographic references

All bibliographic references cited in the text must be listed in the References section. Citations must follow the IEEE (Institute of Electrical and Electronics Engineers) format.

You may consult the materials provided by the Francisco José de Caldas District University Library System or the official IEEE documentation.

ARTICLE SUBMISSION

Authors must submit their articles through the application Open Journal System in digital format, attaching the cover letter and the article-authors format.

Cover letter

The article must be submitted with a cover letter addressed to the director and editor of the journal, Engineer Lely Adriana Luengas Contreras, including:

- Specific request to consider your article to be published in Tecnura journal.
- Full title of the article.
- Full names of all the authors of the paper.
- Certification of the originality and unpublished character of the paper.
- Exclusivity of submission to Tecnura journal.
- Authoring confirmation with signature of all the authors.

This letter must be signed by all the authors, scanned and sent with the remaining requested documents.

Article-authors information format

The article has to be submitted with an information format about the article and its authors which can be downloaded from the web page of Tecnura journal http://revistas.udistrital.edu.co/ojs/index.php/Tecnura/index, in the section "Forms and Documents". It is important to complete all the fields of information requested, some of them have comments to clarify better what is being requested. The format must not be scanned.

Article

Article in digital format (Word 2003 and later editions) that complies with all the presentation rules described in chapter three, "Article structure", of this guide of instructions for authors.

PUBLICATION PROCEDURE

The procedure to be followed by Tecnura journal for the evaluation and possible publication of the papers sent by the authors is the following in chronological order:

1. Delivery of the article with the cover letter and the information format by the authors.
2. Notification to the author about the reception of the article.
3. Verification of the presentation rules by the monitor of the journal.
4. Notification to the author about the evaluation of the presentation rules.
5. Submission of corrections made by the authors related to the evaluation of presentation rules.
6. Submission of the articles to the selected arbitrators.
7. Notification of the beginning of the arbitration process of the article.
8. Notification to the authors about the decision made by the editorial committee, and about the evaluations made by the arbitrators.
9. Delivery of the corrections made by the authors with respect to the evaluations made by the arbitrators.
10. Study of the final version of the article and the evaluations of the arbitrators by the editorial committee.
11. Delivery by the authors of the letter that surrenders right to the editor of the journal.
12. Submission of the version with style corrections and diagramed to the authors.
13. Verification of errors and final approval of the version with style corrections and diagrammed by the authors.
14. Publication of the article in the corresponding number of Tecnura journal.
15. Notification to the authors of the number of interest.
16. Delivery of a copy of the journal to each one of the authors of the published article.

ARTICLE ARBITARION PROCESS

Considering the quarterly periodicity of the journal, the Editorial Committee makes four calls every year for the submission of articles, approximately in the months of February, May, August and November. The articles will be received until the date established in the call.

Once received the articles, the monitor of the journal will make an initial form evaluation to verify the completion of the elements mentioned in this guide of instructions to authors. After receiving again the article with the requested corrections by the journal's monitor, the paper will be submitted to evaluation by three academic peers (through time it is expected to include more external peers to participate in the process).

Each article sent to Tecnura journal is checked by two expert academic peers external to the institution of the authors, by a process of "*Peer-review*" of double blind, guaranteeing the anonymity of authors and evaluators; every paper sent is considered confidential and so it is demanded to evaluators.

Possible conclusions of the result of the evaluation by the judges are only three: publish the article without modifications, publish the article with modifications and not publish the article.

Subsequently, the Editorial Committee takes the decision to publish or not the articles, based on the results of the evaluations made by the assigned arbitrators. In case of contradictions in the evaluations with respect to the publication of an article, the editorial committee will send the article to a third peer and will be inclined for the two evaluations that have the same concept with respect to the publication of the article.

In each call the main author must suggest at least four possible external arbitrators to his work institution evaluators, who must be specialists in the specific topic of the article sent and must have at least Masters level, and at least two must to be international. Potential evaluators can belong to a university or industry, public or private; their complete names must be provided, highest academic formation, institutional affiliation and e-mail. The editorial committee will analyze these four potential evaluators in order to enrich the database of arbitrators of Tecnura journal.

The Editorial Committee of Tecnura journal reserves the right to print, reproduce total or partially the article, as the right to accept or reject it. In the same way, it has the right to make any editorial modification that considers necessary; in this case the author will receive written recommendations from the evaluators. If accepted, authors must deliver the article with the suggested adjustments within the dates given by the journal to guarantee its publication in the programmed number.

CONTACT

For any additional information request, please send an e-mail to Tecnura journal tecnura@udistrital.edu.co, tecnura@gmail.com or by mail to Lely Adriana Luengas Contreras, Director and Publisher of Tecnura Journal, to the following address:

Tecnura Journal
Journals Room, Block 5, Office 305. Faculty of Technology
Universidad Distrital Francisco José de Caldas Transversal 70 B N. 73 a 35 sur
Phone: 571–3239300 Extension: 5003
Mobile: 57–3153614852
Bogotá D.C., Colombia
Email: tecnura.ud@correo.udistrital.edu.co, tecnura@gmail.com
Web page: https://revistas.udistrital.edu.co/ojs/index.php/Tecnura/index