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Journal-Industrial Organization

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Presentation of the content

In the first article we present, *Optimization of processes in a food company through lean tools: Implementation of Just-In-Time and Kanban* by Colorado-Issa, Cinthia Judith, Balderrama-Nieblas, Joel Sebastian, Chacara-Montes, Allan c and Valdez-Sandoval, Aniela Guadalupe, with adscription in the Instituto Tecnológico de Sonora as following article we present *Method for building an Edge-Fog-Cloud system for the Huasteca regenerative agriculture center: a rural production organization* by Hernández-Reséndiz, Rocío Candelaria, Hernández-López, Dalia Rosario, Reyes-Anastacio, Hugo G. and Jiménez-Maldonado, Rosa María with adscription in the Tecnológico Nacional de México – Instituto de Ciudad Valles and Universidad Autónoma de San Luis Potosí as following article we present, *Analysis and prediction of the mass of injection molded parts using factorial models and random forests* by Zavala-Gutiérrez, Jesús, Pérez-Márquez, David, Escalera-Rodríguez, Hugo, González-Hernández, José Antonio and Alcántar-Camarena, Víctor, with affiliation at the Universidad Politécnica del Bicentenario, as next article we present, *Use of slow water in Rio Santiago in Nayarit, through a flow multiplier group with waterotor [G.M.C.W.] for micro electricity generation for the formation of agro parks, in the State of Nayarit* by Jaime-Navarro, Agustín, Bonilla-Alejo, Sergio Raúl and Rodríguez-Rodríguez, Joel with affiliation at the Universidad Tecnológica de Nayarit, as next article we present, *Electromobility in Mexico: Gaps and Opportunities in Public Policies for Electric Vehicles* by Salgado-Conrado, Lizbeth, Pérez-García, Laura Andrea and Álvarez-Macías, Carlos with affiliation at the Universidad Autónoma de Coahuila and Tecnológico Nacional de México/Instituto Tecnológico de La Laguna, as last article we present, *Treated Wastewater: A sustainable alternative with a microplastics perspective* by Tirado-Aguilar, Flor Idalia, González-Moreno, Humberto Raymundo and López-Méndez, María Cristina with affiliation at the National Technological Institute of Mexico / ITS of Misantla.

Content

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Article

Optimization of processes in a food company through lean tools: Implementation of Just-In-Time and Kanban

Optimización de procesos en una empresa alimenticia mediante herramientas lean: Implementación de Just-In-Time y Kanban

Colorado-Issa, Cinthia Judith* [a], Balderrama-Nieblas, Joel Sebastian [b], Chacara-Montes, Allan [c] and Valdez-Sandoval, Aniela Guadalupe [d]

[a] Instituto Tecnológico de Sonora • KZT-8980-2024 • 0009-0003-4072-5727 • 2057920
[b] Instituto Tecnológico de Sonora • NVL-7676-2025 • 0009-0005-0812-3173
[c] Instituto Tecnológico de Sonora • LBI-6576-2024• 0000-0002-0567-0017• 282326
[d] Instituto Tecnológico de Sonora • NUQ-2396-2025 • 0009-0002-8375-3843• 2148529

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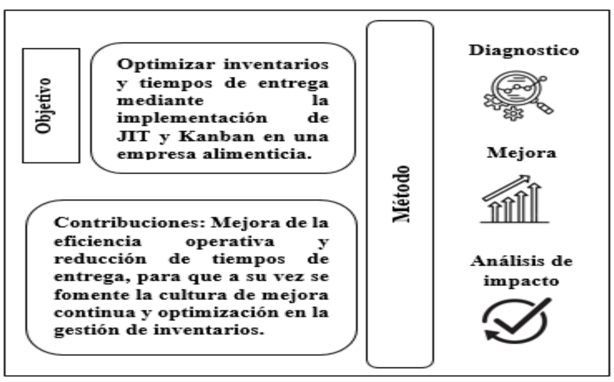
* ✉ [cinthiacoloradoissa@gmail.com]

Abstract

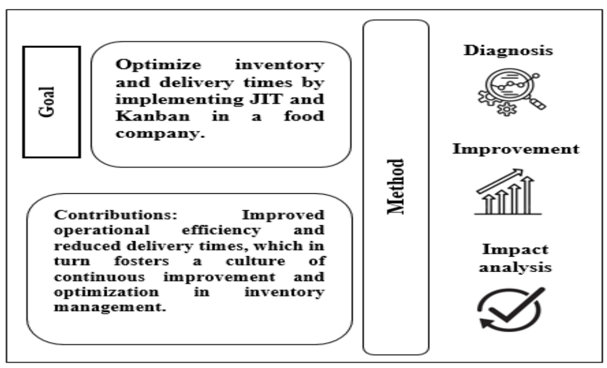
This article presents the implementation of Lean manufacturing tools, specifically Just-In-Time [JIT] and Kanban, in a food company in Navojoa, Sonora. The company faced inefficiencies in inventory management and delivery times, which negatively impacted product quality and customer satisfaction. Through a structured methodological approach, key stages of the production process were mapped using SIPOC, bottlenecks were identified, and improvements were designed based on simulated demand forecasting. The application of JIT allowed synchronization of production with actual demand, while the use of visual Kanban boards improved the flow of materials and communication between workstations. The results showed a reduction of 8.3% in cycle time, 14% in work-in-process inventory, and 47.8% in final product defects. This study demonstrates the viability of applying Lean principles in small food enterprises and provides a replicable model for other companies seeking operational efficiency.



Lean Manufacturing, Just-In-Time, Kanban

Resumen

Este artículo presenta la implementación de herramientas de manufactura esbelta, específicamente Just-In-Time [JIT] y Kanban, en una empresa alimenticia ubicada en Navojoa, Sonora. La organización enfrentaba ineficiencias en gestión de inventarios y en los tiempos de entrega, afectando la calidad del producto y la satisfacción del cliente. Mediante un enfoque metodológico estructurado, se mapearon etapas clave del proceso productivo usando SIPOC, se identificaron cuellos de botella y se diseñaron mejoras con base en un pronóstico simulado de demanda. La aplicación de JIT permitió sincronizar la producción con la demanda real, mientras que el uso de tableros visuales Kanban mejoró el flujo de materiales y la comunicación entre estaciones. Los resultados mostraron una reducción del 8.3% en el tiempo de ciclo, del 14% en inventario en proceso y del 47.8% en defectos del producto final. Este estudio demuestra la viabilidad de aplicar Lean en empresas pequeñas del sector alimenticio.



Manufactura Esbelta, Just-In-Time, Kanban

Area: Advocacy and attention to national problems

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Introduction

In a business environment characterised by growing competition and dynamic consumer demand, organisations must adopt strategic approaches that ensure operational efficiency, flexibility and quality. One of the most influential and effective methodologies in this context is lean manufacturing, which originated in the Toyota Production System [TPS] developed by Taiichi Ohno in the 1940s and 1950s. This approach focuses on eliminating waste, standardising processes and generating value from the customer's perspective [Ohno, 1988; Womack & Jones, 2003; Monden, 2011].

Within the framework of lean manufacturing, one of the key methodologies is the Just In Time [JIT] system, which aims to produce exactly what is needed, at the right time and in the required quantity, minimising inventories and reducing waiting times. This philosophy allows production processes to be synchronised with actual demand, promoting a continuous flow of materials and improving operational efficiency [Díaz et al., 2023].

In this context, the kanban system has established itself as a fundamental tool for the implementation of JIT. According to Arango et al. [2015], kanban is a production management technique based on a ‘pull’ system, which replaces centralised scheduling with self-management of processes.

The operating principle of kanban is to produce and transport only what is required by the consuming processes, keeping only the quantities necessary to ensure continuity of flow in circulation. If consumption is interrupted, production stops automatically, which contributes significantly to waste reduction. In addition, this system simplifies information management, as it is not necessary to draw up detailed plans for each process; it is sufficient for each subsequent stage to remove the parts or products it needs directly from the previous stage, which reinforces the agility and efficiency of the production system.

The food industry, due to its demands for freshness, traceability and health control, has been one of the sectors where the application of lean tools has become most relevant.

According to Dora et al. [2013], food companies that adopt these tools experience an average reduction of 30% in cycle times and a 25% improvement in their operating costs.

A specific case is that of a small café and board game club in Poland, where the implementation of lean management resulted in tangible improvements: the total cost of a meal decreased by 15% and delivery times for meal preparation were reduced by approximately 55%. A 62% decrease in labour costs for specific products was achieved, along with a reduction of about 53% in the number of operations required and the recovery of approximately 30% of kitchen space. In addition, kitchen inventories decreased by between 40% and 65%, contributing to a significant reduction in the spoilage of fresh ingredients [Gładysz et al., 2020].

Another case study is that of Bardales & Becerra [2024], which faced losses due to delays in the delivery of supplies, affecting the preparation of dishes and reducing sales on weekdays. Between October 2023 and March 2024, 23.14% of working days saw late deliveries, representing a 13.76% loss in sales. To address this issue, the Just in Time [JIT] methodology was implemented in inventory management. After its application, a 15% increase in sales, a 50% reduction in customer complaints, a 10% decrease in shrinkage, and a significant improvement in delivery times and supplier relations were projected.

However, the implementation of methodologies such as Just in Time continues to be a challenge for many micro, small, and medium-sized enterprises [MSMEs] due to structural barriers such as limited capital availability, poor staff training, and resistance to organisational change [Smith, 2019; Bhasin, 2012]. These operational constraints often translate into recurring inefficiencies, such as overproduction, excessive inventory accumulation, process bottlenecks, and reduced adaptability to market variations. The company under study has faced various operational problems that affect its productive performance, such as accumulation of work-in-process inventory, downtime between workstations, and defects in the final product. These inefficiencies limit its ability to respond quickly to demand and compromise the quality of customer service.

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Given this scenario, the implementation of two key tools of the lean approach, Just-In-Time [JIT] and Kanban, is proposed with the aim of optimising production flow management, reducing waste and aligning operations with actual market demand.

The study was carried out in a Mexican micro-enterprise in the food sector, located in southern Sonora, dedicated to the production and marketing of artisanal foods. The organisation operates under a batch production system, has three main workstations [preparation, assembly and packaging], and works morning and afternoon shifts. These types of inefficiencies not only increase operating costs, but also deteriorate the customer experience and directly affect business competitiveness [Hines & Taylor, 2000].

Methodology

This research was developed using an applied, descriptive, and non-experimental approach aimed at diagnosing, intervening, and evaluating a real production process within a food sector company, with the objective of implementing lean manufacturing tools and analysing their impact.

The methodology was divided into three main phases:

First phase: Initial diagnosis of the process.

The first step in the procedure is to diagnose the current state of the process, which will allow us to understand how the production system actually operates, identify its key components and detect possible areas for improvement, using the tools shown below:

- SIPOC process mapping. It begins by selecting the process, identifying suppliers, inputs, defining and documenting the current process, detecting outputs or finished products, and finally determining the customers who benefit from the process and receive the outputs.

Second phase: Intervention through lean improvements.

The second step consists of designing and implementing improvements based on the findings of the diagnosis.

Solutions aligned with the lean philosophy are proposed, focused on optimising workflow, reducing waste, and improving operational efficiency, using the tools shown below:

· Demand analysis and production design [Just-In-Time]. A demand analysis will be performed using a simulated forecast model, which will be based on simple moving averages of 3 and 5 weeks. Based on this forecast, a production plan will be designed in line with the principles of the Just-In-Time system, with the aim of producing only what is necessary according to estimated demand, avoiding excess inventory and reducing waste.

- Implementation of the Kanban system. A kanban system will be implemented as a visual management tool to control the workflow between the stations of the production process. To this end, Kanban cards will be designed to indicate the type of product, quantity required and destination station.

These cards will be placed in physical containers or visible boards, allowing each station to request only what is necessary at the right time. This pull system will seek to reduce work-in-process inventory, minimise waiting times and improve synchronisation between preparation, assembly and packaging activities.

Third phase: Impact and results analysis.

The third step of the procedure will consist of a quantitative and qualitative evaluation of the results obtained after the implementation of the improvements. This stage will allow us to measure the impact of the proposed actions on the performance of the process, both in operational terms [times, inventories, production] and in aspects related to the perception of the personnel involved. All of the above will be carried out using the following principles and indicators:

· Cycle time reduction. Cycle time will be measured before and after the implementation of the improvements, considering the total time from the start to the end of the production process. Comparing both results will allow us to evaluate whether the actions taken succeeded in reducing the total time required to complete a production batch.

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- Work in progress and overproduction. The number of units in progress and surplus product will be recorded before and after the intervention. This information will make it possible to identify whether the implementation of the Just-In-Time and Kanban systems contributed to reducing accumulated inventory levels and avoiding unnecessary production.

- Product quality. The number of defective products generated before and after the implementation of the improvements will be evaluated. This comparison will determine whether the actions taken had a positive impact on reducing errors and increasing product compliance with established quality standards.

- Production capacity per shift. The number of units produced per shift before and after the implementation of the improvements will be analysed. This indicator will identify whether the tools applied contributed to increasing process productivity and making more efficient use of the time available in each working day.

- Staff evaluation. A staff evaluation was carried out to ascertain their perception of the changes implemented. To this end, a measurement tool was applied to identify the level of acceptance, understanding and adaptation of the work team to the new operational dynamics.

Results

The analysis and interpretation of the results obtained after applying the proposed methodology are presented below. The findings are structured according to the phases of the proposed procedure, with the aim of evaluating the impact of the improvements implemented in the production process.

In particular, the effects of incorporating Just-In-Time [JIT] and Kanban tools are analysed by monitoring key indicators. The results were obtained from direct observation and surveys of operational staff.

First phase: Initial diagnosis of the process.

- SIPOC process mapping.

The SIPOC tool was used to obtain an overview of the process. This tool made it possible to identify the key elements involved in the company's value stream.

Box 1

Table 1

SIPOC diagram of the current process

Supplier	Entrance	Process	exit	Custome r
Local suppliers	Ingredients	Preparation Assembly Packaging Warehouse	packaged product	Retail customer
Operational staff	Labour	Cooking Assembly Labeling Refrigeration	Product ready for shipping	Final consumer Intermedia te agent

Bottlenecks were detected at the assembly station due to sequential dependence on baking and a lack of standardisation of tasks. In addition, downtime was observed due to waiting for materials, especially during packaging. There was also a tendency towards overproduction, which increases storage costs.

Second phase: Intervention through lean improvements.

- Demand analysis and production design [Just-In-Time].

Since the company did not have sufficient historical records, a simulated forecast model was used to estimate weekly demand, based on simple moving averages over 3 and 5 weeks. This forecast was used to design the production plan.

Box 2

Table 2

Weekly demand [8 weeks]

Semana	Unidades demandadas
1	115
2	130
8	118
4	123
5	122
6	127
7	120
8	126

The overall average was 125 units per week, which served as the basis for establishing a JIT system, reducing in-process inventories and adjusting production times to the actual rate of consumption.

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The analysis following the application of demand smoothing reveals a considerable reduction in peaks, as it works with parameters that are tighter and closer to the average, instead of handling such wide ranges as initially. This allows more balanced sales margins to be maintained as shown in Figure 1.

Box 3

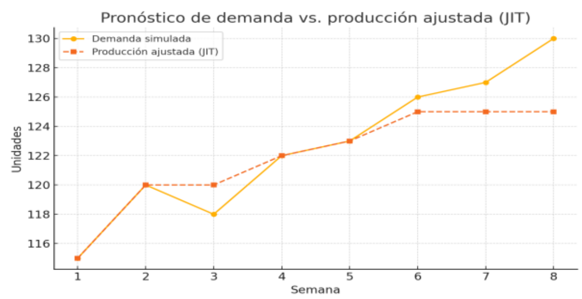

Figure 1
Demand forecast vs. adjusted production [JIT]
Source: Own elaboration

- Implementation of the Kanban system.

A dual-container visual Kanban system was designed, incorporating colour-coded cards to facilitate the identification and management of the flow of materials. These cards were strategically placed in the following process areas:

- Raw material warehouse
- Assembly line
- Packaging area

Each card specified the product, batch, minimum quantity and replenishment quantity. In addition, visual control boards were placed to monitor the flow between stations.

Box 4

Descripción del Producto				ID del Producto	
Proveedor					
Cantidad		Lead time		Fecha del Pedido	
				Fecha de Entrega	
Solicitado por			Tarjeta 1 de ---		
			Ubicación		

Figure 2
Kanban card used in production

Third phase: Impact and results analysis.

- Cycle time reduction.

There was a significant decrease in total cycle time, from 120 minutes to 110 minutes, thanks to better coordination between stations and the elimination of downtime. This 8.3% improvement reflects an increase in overall workflow efficiency.

- Work in progress and overproduction.

The implementation of the JIT system allowed production to be aligned with simulated demand, reducing work in progress inventory from 150 units to 129 units, an improvement of 14%. In addition, the percentage of overproduction, which was initially 10%, was reduced to just 2%, minimising the risk of expired or non-rotating products.

- Product quality

The number of defective products [due to deformation, incorrect baking or damaged packaging] decreased from 2.3% to 1.2%, representing an improvement of 47.8%. This was achieved through the standardisation of tasks and better communication between stations using the Kanban visual system.

- Production capacity per shift

The reorganisation of the flow and the elimination of redundant processes allowed for an increase in daily production capacity without increasing resources. Production rose from 200 units per shift to 218, a 9% increase in productivity.

- Staff evaluation

A staff satisfaction survey was conducted, consisting of five closed questions with a Likert scale. Eighty-five per cent of workers indicated that they felt more comfortable with the new work organisation, highlighting improvements in:

- Clarity of roles
- Communication between stations
- Reduced operational stress
- Ease of detecting errors before they affect the final product

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Box 5

Table 3

Comparison of indicators before and after improvement

Indicator	Before the upgrade	After the upgrade	Variation [%]
Cycle time [min]	120	110	8.3
	30	25	16.7
Waiting time between stations [min]	10%	2%	80
Percentages of overproduction	150	129	14
In-process inventory [units]	2,3%	1,2%	47,8
Defective products	200	218	9

Conclusion

The results of this research show that the implementation of Lean tools, specifically Just-In-Time [JIT] and Kanban, significantly optimises production processes in companies in the food sector, even in small-scale contexts such as local micro-enterprises.

Through a structured methodological approach, it was possible to accurately diagnose the operational deficiencies of the process, design an intervention aligned with actual demand, and quantitatively evaluate the benefits achieved.

One of the most notable achievements was the reduction of the total cycle time by 8.3%, attributed to better synchronisation between stations and the elimination of waiting times. Likewise, a 14% decrease in work-in-progress inventory and a 47.8% reduction in final product defects were achieved, which translates not only into efficiency but also into improved quality and customer satisfaction.

The simulated forecasting model made it possible to structure production according to JIT principles, eliminating overproduction [reduction from 10% to 2%] and ensuring that each unit manufactured had a predicted demand.

On the other hand, the visual Kanban system proved to be a powerful tool for organisation and internal communication, as it facilitated the detection of shortages, allowed for the standardisation of supply replenishment, and contributed to the improvement of the working environment.

In addition to the technical benefits, there was an improvement in staff perception, with 85% reporting a greater understanding of their roles, better communication, and a decrease in operational stress levels. This human component is key to the sustainability of any continuous improvement strategy.

Therefore, we conclude that:

Lean tools can be adapted and applied effectively in small businesses.

Their implementation does not require advanced technology, but rather proper planning, training, and follow-up.

The results are visible in both hard indicators [time, defects, inventory] and soft indicators [internal satisfaction, team commitment].

Finally, this experience can serve as a replicable model for other SMEs in the food sector seeking to optimise their operations without the need for large investments, based on principles of order, flow, and continuous improvement.

Acknowledgements

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Abbreviations

JIT – Just-In-Time
TPS – Toyota Production System
WIP – Work In Process
VSM – Value Stream Mapping
5S – Sort, Set in Order, Shine, Standardise and Sustain Discipline.

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Article

Method for building an Edge-Fog-Cloud system for the Huasteca regenerative agriculture center: a rural production organization

Método para la construcción de un sistema Edge-Fog-Cloud para el centro de agricultura regenerativa de la huasteca: una organización de producción rural

Hernández-Reséndiz, Rocío Candelaria * [a], Hernández-López, Dalia Rosario [b], Reyes-Anastacio, Hugo G. [c] and Jiménez-Maldonado, Rosa María [d]

[a] ROR Tecnológico Nacional de México – Instituto de Ciudad Valles• NBX-4659-2025• 0009-0009-3853-161X, 1311900
[b] ROR Tecnológico Nacional de México – Instituto de Ciudad Valles • T-2470-2018 • 0000-0002-27515886
[c] ROR Universidad Autónoma de San Luis Potosí• 13320483 • 0000-0002-9003-6765• 396373
[d] ROR Tecnológico Nacional de México – Instituto de Ciudad Valles •396373

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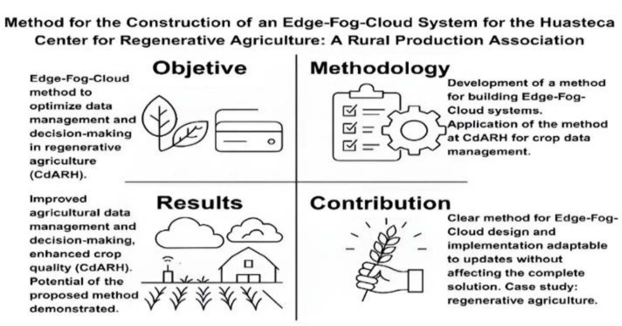
* ✉ [cinthiacoloradoissa@gmail.com]

Abstract

The Edge-Fog-Cloud architecture optimizes distributed data processing by integrating computing from data acquisition to results visualization. Given the need to select appropriate technologies for its design and implementation, especially in agriculture, this research proposes a method for building such systems. This method facilitates the choice of techniques and technologies based on contextual needs, allowing for updates without altering the overall solution. A prototype developed for the Regenerative Agriculture Center of La Huasteca aims to optimize crop data management, demonstrating the method's potential to improve decision-making and quality. This initiative is part of the Tec Huasteca Potosina Node for the Promotion of the Social and Solidarity Economy, fostering regional territorial development.



Edge-Fog-Cloud, Regenerative Agriculture, Construction Method

Resumen

La arquitectura *Edge-Fog-Cloud* optimiza el procesamiento de datos distribuidos, integrando el cómputo desde la adquisición de datos hasta la visualización de resultados. Ante la necesidad de seleccionar tecnologías adecuadas en su diseño e implementación, especialmente en la agricultura, esta investigación propone un método para construir estos sistemas. El método facilita la elección de técnicas y tecnologías según las necesidades del contexto, permitiendo actualizaciones sin alterar la solución global. Un prototipo desarrollado para el Centro de Agricultura Regenerativa de la Huasteca busca optimizar la gestión de datos de cultivo, demostrando el potencial del método para mejorar la toma de decisiones y la calidad. Esta iniciativa forma parte del Nodo de Impulso a la Economía Social y Solidaria Tec Huasteca Potosina, impulsando el desarrollo territorial de la región

Edge-Fog-Cloud, Agricultura Regenerativa, Método de Construcción

Area: Strengthening the scientific community

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Introduction

This research proposes a method for building Edge-Fog-Cloud systems, with the aim of addressing the lack of structured guidelines to facilitate the selection, design, and implementation of distributed technological solutions, particularly in regenerative agriculture. This architecture combines three computational levels that optimise the data processing life cycle: from acquisition to visualisation in the cloud.

Edge computing refers to the processing and storage of data as close as possible to the user, reducing latency and improving response times in applications such as transport, health, and smart cities [Sánchez-Gallegos et al., 2020; Sodhro et al., 2019; Shi et al., 2019; Banafa, 2022].

This approach is key for distributed and real-time systems. ***Fog computing*** acts as a bridge between the edge and the cloud, enabling local processing through nodes close to IoT devices.

This layer offers advantages such as contextual knowledge and low latency [National Institute of Standards and Technology, 2018; Kalyani & Collier, 2021; Iorga et al., 2018; Cantor Albarracín, 2020; Hunko et al., 2023], operating on infrastructures such as WiFi or LAN networks.

For its part, cloud computing provides a scalable infrastructure that allows data to be stored, analysed and consulted from anywhere, favouring web-based applications and intensive analysis platforms [Gomathi et al., 2022; Cárdenas, 2022]. The term was coined in 2006 by Google and Amazon, and encompasses public, private, hybrid, and community models [De Donno et al., 2019].

The evolution of these three approaches has enabled their adoption in contexts such as the **Internet of Things [IoT]**, smart cities and manufacturing, where real-time decision-making is critical [Kumar et al., 2020]. The Edge-Fog-Cloud combination provides a comprehensive solution for hyperconnected environments, such as agriculture, leveraging smart sensors, mobile devices, and wireless networks [Delgado, 2020].

This work implements the proposed method at the **Huasteca Regenerative Agriculture Centre [CdARH]**, demonstrating that a well-structured distributed architecture can improve operational efficiency, decision-making and resource use in rural organisations.

Methodology and Architecture of the Prototype

The proposed method for implementation is divided into three main phases: Edge, Fog, and Cloud, which address specific stages of the data processing life cycle.

Edge phase: Initially, data collection at the CdARH regarding soil temperature and humidity values is done manually, with measurements collected by operators on site. Each operator fills out a paper form and submits it to the office.

These forms are entered into a computer in the form of spreadsheet files [xlsx or comma-separated [CSV] formats]. Due to the initial absence of an automated sensor infrastructure, this method represents the primary input of data.

For the edge computing environment in the case study, the following processes were considered:

Data acquisition via web application [manual entry]: Temperature and humidity collection was maintained manually by users/operators; however, a web application containing the digital version of the form previously used was developed for processing.

This dynamic form allows administrators to enter data according to the collection frequency [every two weeks or every three months], records the data to be measured [each data item must specify the possible values it will contain], and stores it on a server [*fog*].

This stage continues to be part of Edge Computing, as it involves data entry from the *frontend* before being sent for processing and storage.

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Box 1

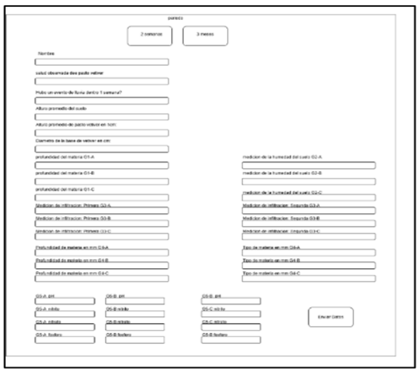

Figure 1
Layout of the dynamic form for data registration**.**

The form workflow is described as follows:

1. **Dynamic registration interface:** Allows the administrator to enter data flexibly, depending on the frequency of collection [e.g. every two weeks or every three months]. The form fields can be adapted to the needs of each data collection.

2. **Validation and pre-processing:** Validations are performed on the front end to ensure that data is captured correctly before being sent to the database.

3. **Sending data to the API:** Once the form is completed, the data is sent to the back end via an HTTP request, where it will be processed and stored.

The method described can be used by the web interface and via sensors.

Data acquisition via mobile devices or sensors: The method is designed so that data acquisition can be used in this way; however, for the purposes of the case study, only simulation was used.

The devices deployed in the environment must transmit data via wireless networks [Wi-Fi, Bluetooth or mobile data] to a centralised device/hub [*Fog*].

In order to standardise the content of the messages, the following message structure is proposed:

Box 2


```
{
    "id": "XX:XX:XX:XX:XX:XX", // Dirección MAC del dispositivo o identificador
único
    "Timestamp": "YYYY-MM-DD HH:MM:SS.sss", // Fecha y hora
    "valores": {
      "parametro_1": {"tipo": "valor"},
      "parametro_2": {"tipo": "valor"}
      // Se pueden agregar más parámetros según sea necesario
    }
```


Figure 2
JSON for Data acquisition through mobile devices or sensors.

The detailed description of the fields of the structure is shown below:

Id: Contains the unique MAC address of the sensor device or specific identifier that allows tracking the source of the data.
Timestamp: This string field records the exact date and time at which the reading was taken, following the format YYYYY-MM-DD HH:MM:SS.ss. Accuracy down to milliseconds allows for detailed temporal analysis.

Values: This field is a JSON object form, which contains the readings of the different parameters that are measured by the sensor. Where the type is the name of the parameter [e.g. 'temperature', 'humidity'] and the value is the measurement.

Figure 3 represents the web site login process, corresponding to the Edge stage within the system architecture. This stage is key, and only administrators have access to the platform to manage data logging.

Box 3

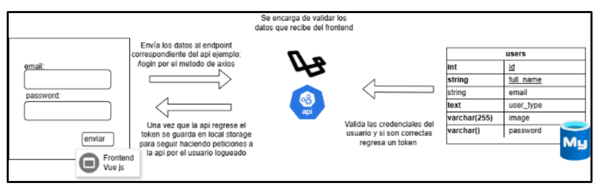

Figure 3
Authentication scheme in the system

The authentication process works as follows: **Login interface:** The administrator user enters their credentials [email and password] in the *login* interface of the *frontend*, developed with Vue.js 5.0.8.

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Communication with the API: The credentials entered are sent to the backend, developed with Laravel 12, via an HTTP request using Axios 1.8.1.

Database validation: The backend verifies the credentials by querying the users table in the MySQL 8.4.0 database. If the data is correct, the server generates an authentication token, which is returned to the frontend.

Token storage: The token received is stored in the browser's Local Storage and cookies, allowing the authenticated user to make subsequent requests to the API without having to log in again.

This scheme represents the last phase within Edge Computing, since, after this step, the information will be processed in the Fog node before its final storage in the cloud.

Fog phase: The Fog phase acts as an intermediary between the Edge and the Cloud, carrying out the initial processing of the data. At this stage, cleaning and filtering techniques are applied to eliminate outliers and ensure the quality of the information before it is transmitted to the next phase.

The workflow in the fog is as follows:

1. **Data reception:** The data is sent by the client in CSV files via email. A computer acts as a collection point and temporary storage for the files.

2. **Pre-processing:** The data is validated and cleaned to ensure its quality and consistency. The necessary transformations are carried out for its correct integration with the cloud storage system.

3. **Sending data to the cloud**: Once processed, the data is uploaded to the database hosted on the web server. The information is only accessible to the administrator from a section of the website.

Cloud phase: Finally, the cloud is responsible for storing and displaying the data. The choice between public or private cloud is considered, depending on the available resources and the client's requirements.

The workflow in the cloud is as follows:

1. **Storage in the database:** The data pre-processed in the fog stage is stored in a database in the cloud, ensuring its availability and persistence.

2. **Access to information via the website:** A web interface is implemented to allow information to be consulted in an organised manner. Visualisation is restricted to users with administrative permissions, ensuring data security.

3. **Data presentation:** The information is displayed in dynamic tables to facilitate analysis. Graphical visualisation tools can be integrated to interpret the data in a specific way.

The use of cloud technologies allowed remote access to information, ensuring that data is always available for consultation and analysis without the need to rely on a local device.

The workflow at this stage is:

1. **Access to the system:** An authorised user accesses the platform through a web browser, connecting to the site's URL.

2. **Connection to the cloud database**: The information consulted comes from a database hosted on a remote server, ensuring the availability and persistence of the data.

3. **Visualisation of information**: The data is presented in dynamic tables and interactive graphs within the website, facilitating its analysis and monitoring.

To facilitate the understanding of the data received and analysed on the website, a section dedicated to graphical visualisation was implemented. These graphs are specifically designed to show the evolution of the data over time.

The key functionality of this section is the ability to select a specific date range. This allows system administrators, upon authentication, to focus their analysis on periods of particular interest.

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Tools and Technologies Used

The following tools and technologies were used to carry out the simulation and implementation of the authentication system:

Python 3.13.2: This programming language was used to develop the sensor simulator code, due to its wide availability of libraries for numerical simulation and data management.

Login interface [Frontend]: The registration interface for the administrator user was developed using the Vue.js 5.0.8 framework, chosen for its responsiveness and efficiency in building dynamic user interfaces.

Backend [API]: The application backend was implemented with the Laravel 12 framework, which facilitates the development of robust and secure APIs. Communication between the frontend and backend was carried out through HTTP requests using the Axios 1.8.1 library.

Database: The MySQL 8.4.0.04 relational database was used to store and verify user credentials. The backend queries and validates the login information.

Authentication: Once the backend has verified the credentials, it generates an authentication token allowing the user to make requests.

Login interface: The administrator user enters their credentials [email and password] in the frontend login interface, developed with Vue.js.

Communication with the API: The credentials entered are sent to the backend, developed with Laravel, through an HTTP request using Axios.

Database validation: The backend verifies the credentials by querying the users table in the MySQL database.

If the data is correct, the server generates an authentication token, which is returned to the frontend.

Token storage: The received token is stored in the browser's Local Storage, allowing the authenticated user to make subsequent requests to the API without having to log in again.

Case study: CdARH

The proposed method was applied at the Huasteca Regenerative Agriculture Centre [CdARH], a rural production association dedicated to the implementation of sustainable agricultural practices.

The CdARH requires an efficient data management system to optimise crop control and improve decision-making.

Vetiver grass was selected as the object of study due to its importance in regenerative agriculture and its ability to provide relevant information about soil conditions.

System Testing and Response Time Analysis Real sensors:

Tests were carried out with real sensors, monitoring temperature and humidity for 10 minutes. These tests yielded 600 temperature records, validating the system's ability to handle real-time data within a range of 1 to 2.5 seconds.

These configurations were obtained using the times established by the CC1350 SensorTag rapid development and prototyping kit from Texas Instruments as a basis. This device integrates multiple environmental and motion sensors and wireless connectivity, allowing for easy testing and prototyping of Internet of Things [IoT] applications [Wakeup et al., 2016].

The CC1350 SensorTag transmits the collected data using Bluetooth Low Energy [BLE]. The latency of this system, defined as the time elapsed from the capture of the data by the sensor to its reception and processing, was considered as a reference for establishing the times in this research. To reduce latency, the recommendations of Texas Instruments were followed, keeping the sensor at a distance of 5-10 metres. However, it was identified that the sensors used were of a test type, unsuitable for the high temperatures of the Regenerative Agriculture Centre or an outdoor environment [exposed to the elements].

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RENIECYT: 1702902

Server testing:

To evaluate the scalability of the system and determine its maximum capacity within the server, tests were performed with the simulator, progressively increasing the number of simulated sensors to 6, 64, and 128.

The development of code to monitor API performance and statistical analysis of response times provided crucial quantitative data to validate the efficiency of the system.

The consistency between the simulator results and the tests with real sensors validates the accuracy of the simulator as a testing tool. However, the limitation of the test sensors highlights the need to select sensors that are suitable for the real environment.

The statistical analysis of API response times, documented in Excel spreadsheets, provides a solid basis for future improvements and for selecting appropriate hardware. This quantitative data is essential for improving system reliability in a production environment.

Results

Phase 1 *Edge:* Table 1 presents a summary of the statistical response time metrics obtained for each scenario within the server. The results with six sensors, representing the initial scale required for implementation at the CdARH, were satisfactory, showing an average response time of 0.492 seconds and a maximum of 0.750 seconds, both below the critical threshold of 2.5 seconds [set by the sensor used for testing].

When simulating 64 sensors, an increase in the average [0.582 seconds] and maximum [1.690 seconds] response times was observed, still remaining within the acceptable range. However, when simulating 128 sensors, the average response time rose significantly to 1.353 seconds, and the maximum time exceeded the 2.5-second limit, reaching 3.031 seconds.

These findings indicate that the system begins to experience saturation in its processing capacity when handling 128 sensors simultaneously, which could result in request queuing and poor performance in a real-world environment [for the hardware used].

Therefore, while the system proves to be adequate for the initial scale of the CdARH, the limitations identified with higher loads are crucial for planning future expansions and identifying potential improvements in the infrastructure.

Box 4

Table 1

Comparison of simulated response time metrics for different numbers of sensors on the server.

Metrica	6 capteurs	64 capteurs	128 capteurs
Échantillons	40	40	40
Moyenne [Moyenne]	0.492 s	0.582 s	1.353 s
Écart-type [Std]	0.078 s	0.275 s	0.554 s
Minimum [Min]	0.420 s	0.435 s	0.790 s
Percentile [25%]	0.442 s	0.455 s	0.986 s
Médiane [50%]	0.470 s	0.484 s	1.210 s
75 % du percentile	0.508 s	0.560 s	1.515 s
Maximum [Max]	0.750 s	1.690 s	3.031 s
Dépasse 2,5 s	No	No	Si

Testing in the Local database:

In order to evaluate the performance of the system by directly storing the data generated by the sensors in a local database, extensive tests were carried out by simulating the simultaneous operation of an increasing number of sensors: 6, 64, 128, 192, 256 and 512.

Table 3 presents a detailed summary of the statistical metrics obtained for each of these scenarios, specifically considering the time it takes to save the data for each sensor in the local storage.

The local storage system shows a desirable and stable performance up to 192 sensors connected simultaneously. This limit is defined based on the following criteria

TLow and constant response times: Up to 192 sensors, the average response times remain in the millisecond [ms] range, the average value being 0.00344 s. in the worst case [192 sensors], which is acceptable for local applications.

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b] Controlled range of variation: Although the maximum value recorded in the 192-sensor test reached 0.03368 s., it is still below the 2.5-second range and is therefore considered safe.

c] Moderate increase of the standard deviation: The scatter of the data starts to increase with 192 sensors, indicating the beginning of a possible overload in concurrent processes. To maintain consistency and avoid future degradation, this limit is set as a safe operating benchmark.

d] Prevention of bottlenecks: Although tests have also been carried out with 256 and 512 sensors, these show higher scattering and point times that could grow in real conditions, so it is recommended to keep the system in regular operation up to 192 sensors to ensure stability.

Box

Table 2

Comparison of local database write time metrics for different sensor counts.

Échantillons	**6 s**	**64 s**	**128 s**	**192 s**	**256 s**	**512 s**
Moyenne [Moyenne]	40	40	40	40	40	40
Écart-type [Std]	0.00074 s	0.00149 s	0.00214 s	0.00344 s	0.00537 s	0.01524 s
Minimum [Min]	0.00057 s	0.00216 s	0.00209 s	0.00739 s	0.01220 s	0.05561 s
Percentile [25%]	0.00010 s	0.00014 s	0.00019 s	0.00013 s	0.00011 s	0.00021 s
Médiane [50%]	0.00040 s	0.00032 s	0.00062 s	0.00037 s	0.00058 s	0.00070 s
75 % du percentile	0.00065 s	0.00061 s	0.00125 s	0.00087 s	0.00156 s	0.00163 s
Maximum [Max]	0.00082 s	0.00134 s	0.00298 s	0.00264 s	0.00670 s	0.00694 s
Dépasse 2,5 s	0.00263 s	0.00698 s	0.00805 s	0.03368 s	0.04588 s	0.36093 s
Échantillons	No	No	No	No	No	No

Source Own elaboration based on simulation results with Python..

Response time analysis:

Figure 4 shows the cycle time distribution for the sensor with MAC address 59:E4:A8:4A:7C:EA.

In this representation, the horizontal axis [X-axis] is the cycle time duration in seconds [1], while the vertical axis [Y-axis] indicates the frequency or count of times that a given cycle time was recorded within each interval.

From this distribution, it can be seen that most cycles were completed in approximately 1.2 seconds, indicating adequate sensor performance in most operations with respect to its maximum transfer interval [2.5 seconds].

The dispersion of the distribution suggests some variability in cycle time, with some cycles completing in less than 1 second and others extending to more than 2 seconds.

This could be indicative of the system load affecting these results.

It can be noted that all cycle times evaluated remained within the accepted range [2.5 seconds]. The evaluations showed a maximum of approximately 2.2 seconds, suggesting that the sensor operates within the expected parameters in the controlled experiment simulating six sensors.

Complementing the visual representation of the 'Cycle Time Distribution' [illustrated in Figure 4], a descriptive statistical analysis was performed on the 20 records obtained from sensor 59:E4:A8:4A:7C:EA. In this analysis, the median is fundamental to understanding the central tendency of the data.

For the series of 20 cycle times analysed, the median calculated was 1,161 seconds. This measure is important due to possible outliers [the bars at the extremes, very short or long, which could indicate unusual behaviour or possible simulation problems], i.e. the median not only validates the observed data concentration, but also provides a quantitative and accurate reference for the central behaviour of the sensor cycle process.

[1] Cycle time is the time it takes for the sensor to complete a full cycle of reading, processing, and sending data.

Box

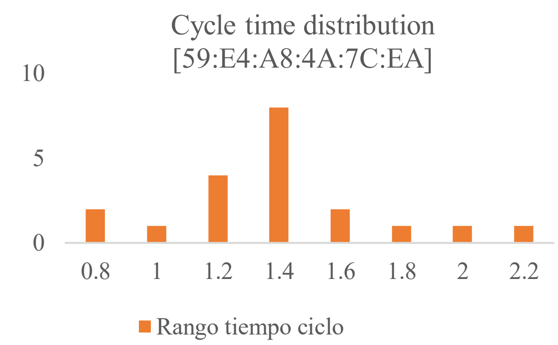

Figure 4

Cycle Time Distribution for the Sensor

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System Deployment

Description of the deployment process:

At this stage, the system was deployed in the corresponding infrastructure. The hardware architecture was configured and prepared to host the software, ensuring that it met the performance, security, and availability requirements.

Conclusions

The fundamental purpose of this analysis and subsequent data visualisation was to provide members of the Huasteca Regenerative Agriculture Centre [CdARH] with a clear and accurate view of progress in the fields. By having access to this historical information and the ability to analyse trends through time graphs, managers can make informed decisions and plan improvements to their agricultural practices, thereby improving management.

These findings are crucial for planning implementation at the CdARH and for future expansions, as it is important to consider the limitations identified with higher loads when designing infrastructure and possible optimisations in the future.

The development of research such as this, which is implemented in collaboration with social organisations, enables access to technological resources for groups of small producers who approach the CdARH Organisation to learn about regenerative farming techniques with technological support for information management, which makes natural resources more efficient and improves decision-making. These techniques contribute to the sustainability of the Huasteco region's farmland, contributing significantly to its mission: To work creatively and constructively with local, regional, national and international partners to protect the environment and regenerate natural resources while strengthening rural economies.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Contribution of the authors

Rocio Hernández, Engineer: Carried out the application of the methodology development, data collection, systematisation of results, and writing.

Dalia Hernández, MAE: Contributed with the project idea, research method and technique.

Hugo Reyes: Contributed to the research method and technique approach.

Rosa: Assisted with article writing, systematisation of results, and fieldwork.

Availability of data and materials

Indicate the availability of the data obtained in this research.

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This study did not receive external funding.

Abbreviations

API	Application Programming Interface
CdARH	Huasteca Centre for Regenerative Agriculture
S	Sensors

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Background

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Article

Analysis and prediction of the mass of injection molded parts using factorial models and random forests

Análisis y predicción de la masa de piezas moldeadas por inyección empleando modelos factoriales y bosques aleatorios

Zavala-Gutiérrez, Jesús [a], Pérez-Márquez, David [b], Escalera-Rodríguez, Hugo [c], González-Hernández, José Antonio [d] and Alcántar-Camarena, Víctor [e]

[a] Universidad Politécnica del Bicentenario • 484943
[b] Universidad Politécnica del Bicentenario 0000-0003-2745-6000 • 297006
[c] Universidad Politécnica del Bicentenario • 439112
[d] Universidad Politécnica del Bicentenario • 719324
[e] Universidad Politécnica del Bicentenario 0000-0002-4279-3120 • 294973

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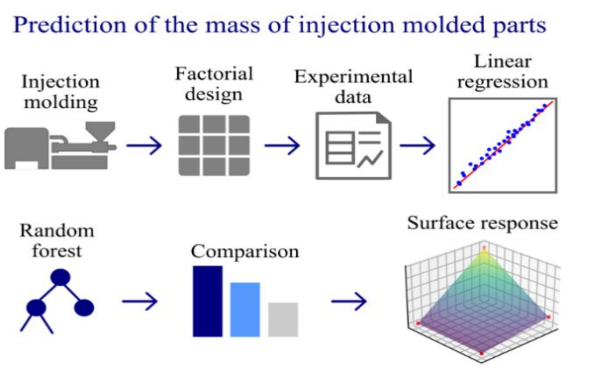
* ✉ [valcantarc@upbicentenario.edu.mx]

Abstract

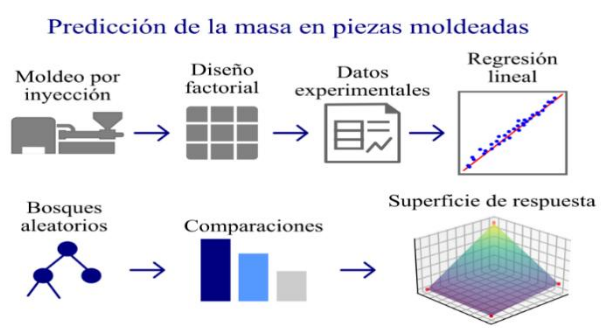
This work presents a combined approach using factorial design of experiments and machine learning models to analyze and predict the mass of parts manufactured by injection molding. A 2^k factorial design was employed to evaluate the effect of four process factors—holding pressure, injection pressure, injection time, and injection speed—on the mass of molded parts. A factorial regression model was constructed and assessed using analysis of variance, showing a high coefficient of determination. Subsequently, a regression model based on random forests was trained, achieving remarkable predictive performance. Both approaches were compared using mean squared error and root mean squared error metrics. The results show that both models are highly accurate. This hybrid approach provides a solid foundation for optimizing the injection molding process in industrial applications.



Injection molding, design of experiments, random forest

Resumen

En este trabajo se presenta un enfoque combinado de diseño de experimentos factorial y modelos de aprendizaje automático para analizar y predecir la masa de las piezas fabricadas mediante moldeo por inyección. Se empleó un diseño factorial 2^k para evaluar el efecto de cuatro factores del proceso, presión de sostenimiento, presión de inyección, tiempo de inyección y velocidad de inyección sobre la masa de las piezas moldeadas. Se construyó un modelo de regresión factorial, el cual fue evaluado mediante análisis de varianza mostrando un alto coeficiente de determinación. Posteriormente, se entrenó un modelo de regresión utilizando bosques aleatorios, obteniendo un desempeño predictivo notable. Además, se compararon ambas aproximaciones mediante métricas de error cuadrático medio y raíz del error cuadrático medio. Los resultados muestran que ambos modelos son altamente precisos. Este enfoque híbrido proporciona una base sólida para la optimización del proceso de moldeo por inyección en aplicaciones industriales.



Moldeo por inyección, diseño de experimentos, bosques aleatorios.

Area: Dissemination of and universal access to science

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Introduction

Injection molding is a widely used manufacturing technique due to its high production efficiency, precision, repeatability, low cost, and design flexibility. This versatility allows for the creation of parts with complex shapes and intricate details [Moayyedian, *et al*., 2018]. The process consists of four main stages: filling, packing, cooling, and ejection [Chen *et al*., 2023; Selvaraj *et al*., 2022].

In the first stage, the resin is heated until it becomes molten and is then injected into the mold at a specific speed until it reaches the transfer position. During this phase, the pressure is a result of the injection speed, filling approximately 95% of the mold volume. In the second stage, the pressure is controlled, and the injection speed is reduced. The cavities are packed by maintaining a constant pressure until the sprues solidify, thereby filling any remaining voids left from the previous stage. Subsequently, the material cools and solidifies, conforming to the shape of the mold cavity. In the final stage, the molded part is ejected from the mold.

Once removed, the parts are inspected to assess their quality. Common defects include flow marks, volumetric shrinkage, weld lines, sink marks, warping, short shots, flash, air bubbles, burn marks, among others [Mourya *et al*., 2023].

There are multiple factors that influence the quality of injection-molded parts. Numerous studies analyzing specific defects can be found in the literature. Hu *et al*. [2023] investigated the development of unstable flow in the injection molding of a polypropylene and polyolefin elastomer blend through short-shot experiments.

Their results showed that the melt flows stably during the initial stage, but the flow front subsequently begins to fluctuate along the thickness direction. The molten material exhibits variations in temperature and shear stress, leading to the formation of flow marks. Otieno *et al*. [2025] proposed the use of design of experiments, computer-aided simulations, and intelligent algorithms to develop a predictive model for warpage and volumetric shrinkage defects based on processing parameters.

Liparoti *et al*. [2023] analyzed the influence of mold temperature on the position and strength of weld lines in the micro-injection molding process. Their experimental studies considered mold temperature, injection pressure, flow velocity, and melt temperature. Additionally, they evaluated the mechanical properties of the test specimens both at the weld lines and in the continuous sections using optical microscopy and tensile testing.

They complemented the studies with numerical analysis to determine the characteristics of the welding lines. Pachorkar *et al*. [2023] studied how to reduce the depth of sink marks in transparent thermoplastic polypropylene products. They considered five variable injection molding parameters: melt temperature, mold temperature, packing time, rib-to-wall ratio, and the distance between ribs and the injection point. The authors implemented a Taguchi design to optimize these factors by treating it as a multi-criteria problem.

The depth of the sink mark on the surface of the part was used as an indicator of product quality and cycle time. Using an artificial neural network model, Zhou *et al*. [2023] were able to predict the occurrence of short shot defects in injection molding. In addition, they investigated the effectiveness of two learning methods. The first model was trained using simulation data, followed by transfer learning with experimental data. In the second approach, only experimental data were used for training.

They determined that the parameters most influencing the short shot defect are injection speed, holding pressure, and material temperature.

These parameters directly affect mold filling and the material ability to flow properly. Fahmi *et al*. [2022] used the Taguchi method to determine the optimal parameters for minimizing burr defects. They proposed a fractional factorial design for three injection molding test cycles using polypropylene. The parameters considered included melt temperature, injection speed, pressure, and injection time.

Their study also identified the parameter configuration that reduces flash defects, as well as the variables with the greatest influence.

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Díaz-Ovalle *et al*. [2020] proposed a computational fluid dynamics [CFD] study to analyze the formation and distribution of bubbles in a foamed polymer part. The results were consistent with experimental data and enabled the prediction of the shape, location, and predominant size of the bubbles.

The proposed methodology could also be applied to study bubble arrangements in more complex geometries, which are directly related to the mechanical properties of the part. Li *et al*. [2021] investigated the effectiveness of external gas-assisted injection molding in reducing burn marks on molded parts. The objective was to compare the burn marks on parts produced using this technique with those produced by conventional injection molding. Image processing was employed to determine the ratio of the burned area to the total surface area of each part.

According to the aforementioned references, injection molding remains a topic of significant interest in the scientific and industrial communities. The primary areas of research focus on defect reduction and process optimization. Although injection molding is a widely adopted manufacturing technique, the process is challenging to control due to the large number of parameters involved, including mold temperature, resin temperature, injection speed, injection pressure, injection time, packing pressure, packing time, cooling time, among others [Zhao *et al*., 2022].

The most commonly employed techniques by researchers include design of experiments [DoE], statistical analysis, computer simulations, and increasingly, machine learning approaches such as artificial neural networks.

This study aims to analyze the influence of holding pressure, injection pressure, injection time, and injection speed on the mass of injection-molded parts. To this end, a 2^k factorial experimental design with two replicates was implemented, resulting in a total of 32 trials. A regression model was developed to estimate the mass of the parts as a function of the four selected process parameters.

Additionally, a random forest [RF] model was trained using the experimental data to predict the mass of the molded parts.

The predictive performance of both methodologies was compared, yielding high coefficients of determination. Finally, surface and contour plots were generated to illustrate the behavior of the most influential factors on the response variable.

Methodology

Injection molding was carried out using a Belken BL130HHD horizontal injection molding machine, designed for the efficient production of plastic components. The equipment is located in the Industrial Design Engineering Laboratory at the Universidad Politécnica del Bicentenario.

The main technical specifications of the machine are summarized in Table 1.

Box 1

Table 1

Technical specifications of the injection molding machine Belken BL130HHD.

Specifications	Value	Unit
Clamping force	130	Ton
Screw diameter	42	mm
Screw L/D ratio	22	-
Shot size	263	cm^3
Injection pressure	152	MPa
Screw speed	220	RPM

Source: https://acortar.link/vAnotB

The injected part is a polypropylene flying disc [frisbee] with a diameter of 220 mm, as shown in Figure 1.

Box 2

Figure 1

Injected plastic part.

Source: own

Design of Experiments is a systematic methodology used to efficiently plan, conduct, analyze, and interpret experiments. Its primary objective is to understand the relationships between input variables [factors] and output responses [results].

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In general terms, DoE involves determining which experiments should be performed and how they should be conducted in order to generate data that, when analyzed statistically, provide insights into how to improve uncertain or variable aspects of a process [Gutiérrez Pulido *et al*., 2012].

In this study, a full 2^k factorial design was employed, meaning a model consisting of k factors, each evaluated at two levels. The input variables considered were holding pressure [P_h], injection pressure [P_i], injection time [t_i], and injection speed [v_i]. The response variable analyzed was the mass of the molded parts [m].

Table 2 presents the values assigned to each parameter at both high and low levels. In the case of the injection speed profile, the percentage distribution across six segments along the screw was specified.

Box 3

Table 2

Injection molding parameter values used in the experimental design

Factor	Unit	Levels	
		High [+1]	Low [-1]
Holding pressure	Bar	20	15
Injection pressure	Bar	80	70
Injection time	s	1.8	1.5
Injection speed profile	% of speed	A	B

Speed profiles	% of injection speed					
A	80	64	51	41	32	26
B	75	62	52	43	36	30

Random forests [RF] are supervised learning algorithms based on ensemble methods, widely applied to both classification and regression problems. Their architecture comprises multiple decision trees, hierarchical structures in which each internal node represents a condition on a feature [e.g., value_1 ≤ a], each branch corresponds to a possible outcome of that condition, and each leaf node produces a prediction [see Figure 2].

These trees operate through successive binary splits of the data, guided by optimization criteria such as Gini impurity or information gain. In a random forest, each tree is trained using a twofold randomization strategy: first, by sampling the training data with replacement [bagging], and second, by randomly selecting a subset of features at each node. This double randomization promotes diversity among the trees, and when their predictions are aggregated, the overall model benefits from reduced variance, improved robustness, and enhanced predictive performance [Chollet, 2021].

The final prediction of a random forest is obtained through consensus: in classification tasks, by majority voting among the trees, and in regression tasks, by averaging their outputs. This aggregation strategy leverages the law of large numbers to stabilize results, thereby reducing both error variance and sensitivity to noise in the data. Furthermore, random forests provide feature importance metrics, which quantify the relative contribution of each predictor variable to the model accuracy.

Box 4

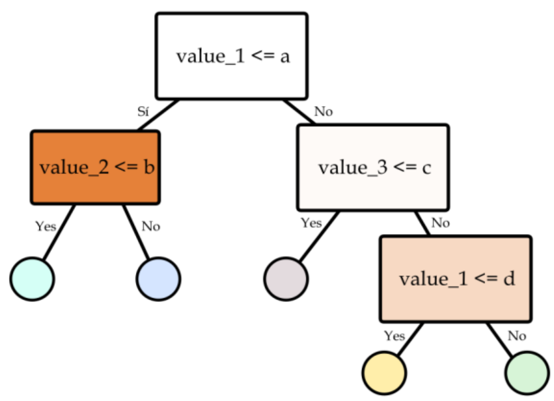

Figure 2

Representation of a decision tree.

Source: own

In the context of predicting the mass of injection-molded parts, this technique is particularly advantageous due to its capacity to model nonlinear relationships, handle high-dimensional data, and maintain robustness in the presence of outliers.

The combination of these attributes enables the algorithm to capture the inherent complexity of the manufacturing process while achieving an optimal balance between predictive performance and computational efficiency.

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Results

A 2^k factorial experimental design was generated using the Python library pyDOE2 [Baudin *et al*, 2024], which is widely recognized for its efficiency and flexibility in creating experimental designs. This library supports the generation of full factorial, fractional factorial, and response surface designs, making it a versatile tool for experiment planning. In this study, two replicates were conducted for each combination of factors. With four factors under consideration, a total of 32 experiments were performed. Following the molding process, the mass of each part was measured. The experimental results are presented in Table 3.

Box 5

Table 3

Design of experiments 2^k and response values for two replicates.

Test	P_h	P_i	t_i	v_i	Mass [g] Rep. 1	Rep. 2
1	-1	-1	-1	-1	62.48	62.47
2	1	-1	-1	-1	62.83	62.71
3	-1	1	-1	-1	61.95	61.73
4	1	1	-1	-1	63.28	63.35
5	-1	-1	1	-1	62.16	62.10
6	1	-1	1	-1	62.51	62.51
7	-1	1	1	-1	62.28	62.25
8	1	1	1	-1	62.82	62.88
9	-1	-1	-1	1	61.87	61.86
10	1	-1	-1	1	62.32	62.33
11	-1	1	-1	1	62.01	61.93
12	1	1	-1	1	62.72	62.67
13	-1	-1	1	1	62.02	62.01
14	1	-1	1	1	62.54	62.48
15	-1	1	1	1	63.75	63.61
16	1	1	1	1	64.78	64.87

Figure 3 presents a Pareto chart illustrating the magnitude and relative importance of the main effects and interactions on the mass of injection-molded parts. The horizontal axis represents the estimated effect values, while the vertical axis lists the factors and their combinations. Holding pressure emerged as the most significant factor, with an effect value of 0.6950, indicating that an increase in this variable substantially increases part mass. This finding aligns with the physics of the injection molding process, as higher holding pressure enhances mold packing, reduces volumetric shrinkage, and consequently increases mass. The interaction between injection time and injection speed also shows a considerable influence, with an effect value of 0.6025.

This suggests that the combination of longer injection times and appropriate injection speeds promotes more complete mold filling, which in turn increases the mass of the molded parts.

Box 6

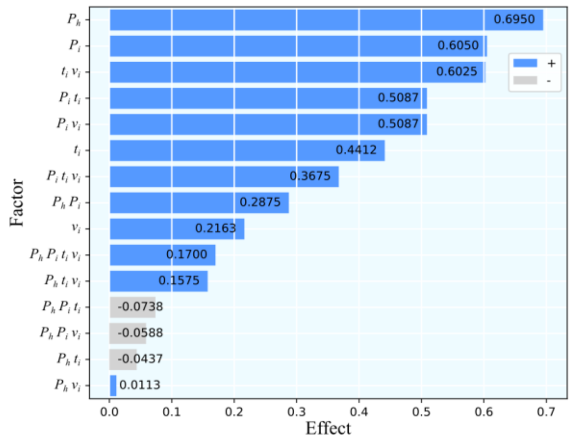

Figure 3

Pareto chart of effects and factors on the mass of injection molded parts.

Source: own

To quantify the relationship between the injection molding process parameters and the mass of the parts, a factorial regression model was developed and fitted. In addition to the main effects of each factor, the model incorporated possible second-, third-, and fourth-order interaction terms, see Equation [1].

The resulting regression equation serves as a predictive tool for estimating part mass as a function of the process variables.

$$m = 62.6275 + 0.3475P_h + 0.3025P_i + 0.2206t_i + 0.1081v_i + 0.1437P_hP_i - 0.0219P_ht_i + 0.0056P_hv_i + 0.2544P_it_i + 0.2544P_iv_i + 0.3013t_iv_i - 0.0369P_hP_it_i - 0.0294P_hP_iv_i + 0.0787P_ht_iv_i + 0.1837P_it_iv_i + 0.0850P_hP_it_iv_i \quad [1]$$

To evaluate the statistical significance of the main effects and interactions on the mass of injection-molded parts, an analysis of variance [ANOVA] was performed on the regression model. Table 4 summarizes the results, including the degrees of freedom [df], sum of squares [sum_sq], mean squares [mean_sq], F-statistic, and p-value. As shown, the p-values for the main factors are all below 0.05, indicating that they exert a statistically significant effect on part mass.

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Among these, holding pressure $[P_h]$ exhibits the greatest influence $[F = 1062.3]$, followed by injection pressure $[P_i]$ and injection time $[t_i]$, with F-values of 805.0 and 428.2, respectively. These results are consistent with previous findings in the literature, highlighting the critical role of these parameters in ensuring proper material compaction and minimizing defects such as voids and shrinkage. Injection time also demonstrates a strong effect, underscoring the importance of its precise control to prevent issues such as incomplete filling or material excess.

In contrast, injection speed $[v_i]$ shows a less pronounced yet still significant effect $[F = 102.8]$, suggesting that while its impact is comparatively smaller, it should not be overlooked in process optimization.

Box 7

Table 4

ANOVA results for the factorial regression model.

Factor	df	sum_sq	mean_sq	F	p-value
P_h	1.0	3.8642	3.8642	1062.3	4.6e-16
P_i	1.0	2.9282	2.9282	805.0	4.1e-15
t_i	1.0	1.5576	1.5576	428.2	5.6e-13
v_i	1.0	0.3741	0.3741	102.8	2.2e-08
$P_h: P_i$	1.0	0.6613	0.6613	181.8	3.7e-10
$P_h: t_i$	1.0	0.0153	0.0153	4.2	5.7e-02
$P_h: v_i$	1.0	0.0010	0.0010	0.3	6.1e-01
$P_i: t_i$	1.0	2.0706	2.0706	569.2	6.2e-14
$P_i: v_i$	1.0	2.0706	2.0706	569.2	6.2e-14
$t_i: v_i$	1.0	2.9041	2.9041	798.4	4.4e-15
$P_h: P_i: t_i$	1.0	0.0435	0.0435	11.9	3.2e-03
$P_h: P_i: v_i$	1.0	0.0276	0.0276	7.6	1.4e-02
$P_h: t_i: v_i$	1.0	0.1985	0.1985	54.6	1.5e-06
$P_h: t_i: v_i$	1.0	1.0804	1.0804	297.0	9.4e-12
$P_h: P_i: t_i: v$	1.0	0.2312	0.2312	63.6	5.8e-07
Residual	16.0	0.0582	0.0036		

Among the second-order interactions, the combinations of injection pressure with injection time $[P_i: t_i,\ F = 569.2]$ and injection time with injection speed $[t_i: v_i,\ F = 798.4]$ stand out, highlighting the critical role of these parameter pairs in determining the quality of the final product. For instance, applying high injection pressure with insufficient injection time may lead to defects such as flow lines or residual stresses.

Similarly, the interaction between holding pressure and injection pressure $[P_h: P_i,\ F = 181.8]$ underscores the need to jointly optimize both pressures to prevent compaction-related issues.

Higher-order interactions also show notable effects. In particular, the third-order interaction $P_i: t_i: v_i$ $[F = 297.0]$ and the fourth-order interaction $P_h: P_i: t_i: v_i$ $[F = 63.6]$ suggest that the synchronization of multiple parameters is essential to controlling complex phenomena such as melt viscosity and thermal behavior during the molding process.

To visualize the combined effect of injection pressure and injection time on the mass of the molded parts, surface plots [Figure 4a] and contour plots [Figure 4b] were generated. In both cases, holding pressure $[P_h]$ and injection speed $[v_i]$ were fixed at their high level [+1].

The surface plot reveals a clear trend: as both injection pressure and injection time increase, the mass of the part rises steadily. This behavior confirms the presence of a significant positive interaction, as previously identified in the ANOVA results. The contour plot, in turn, exhibits an inclined and gently curved shape, indicating that the highest part mass is obtained when both parameters are set at their maximum levels. This observation is consistent with the injection molding process, where higher pressure promotes more complete filling of the mold, while longer injection time helps prevent defects such as incomplete filling or shrinkage.

Box 8

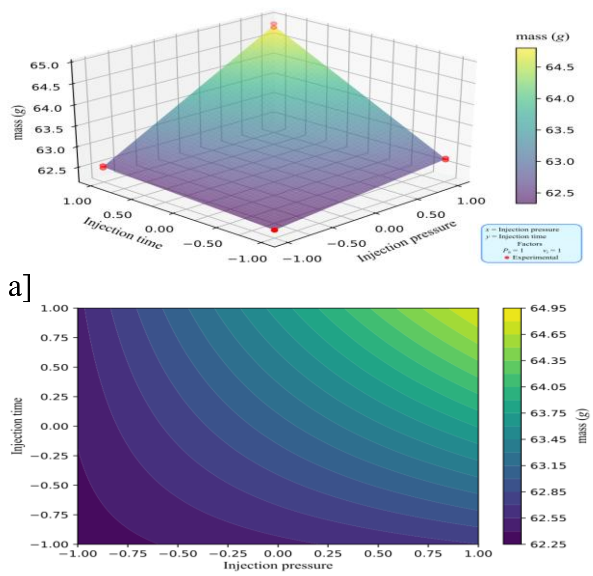

Figure 4

Graphical representation of the variation in mass as a function of injection pressure and time. [a] Surface plot illustrating the relationship between the aforementioned variables, with the factors of sustaining pressure and injection rate constant at their high level [+1]. [b] Contour map showing the interaction between pressure and injection time.

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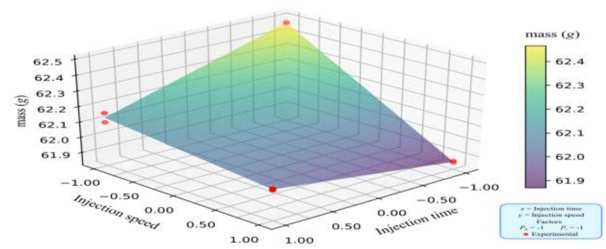
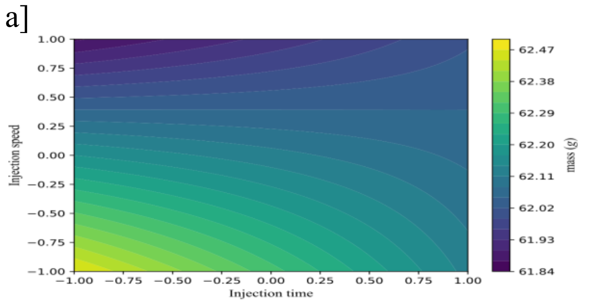
Figure 5a presents the surface plot, and Figure 5b the contour plot, illustrating the interaction between injection speed and injection time on the mass of the molded parts. In this case, holding pressure and injection pressure were fixed at their low level [–1]. The surface plot shows that part mass increases as both injection time and speed rise simultaneously, reaching a maximum value of approximately 62.5 g. This trend aligns with the expected behavior of the injection molding process: longer injection times allow greater material flow into the cavity, while higher speeds ensure efficient filling before solidification occurs. Moreover, the gently sloping shape of the surface indicates a positive interaction between the two factors. This observation is consistent with the ANOVA results, where the $t_i\!:v_i$ interaction exhibited a high F-value, confirming its statistical significance.

Box 9



a]



b]

Figure 5

Graphical representation of the variation in mass as a function of injection velocity and time. [a] Surface plot illustrating the relationship between the aforementioned variables, with the factors sustaining pressure and injection pressure constant at their low level [-1]. [b] Contour map showing the interaction between injection time and speed.

The residual analysis was performed to assess the quality of fit of the proposed regression model. The plot of residuals versus predicted values [Figure 6a] shows a uniform dispersion of points around the zero reference line, with no evident systematic patterns. This indicates the absence of heteroscedasticity, suggesting that the variance of the errors remains approximately constant across different prediction levels.

Similarly, the plot of residuals versus the observation order [Figure 6b] was used to examine the potential temporal or sequential dependence of the errors. The random distribution observed in this graph confirms the absence of significant autocorrelation, thereby supporting the assumption of error independence a particularly relevant condition in models applied to time-dependent or sequential processes.

Finally, the quantile–quantile plot [Figure 6c] shows that the residuals align closely with the theoretical normal distribution line, indicating that the errors are approximately normally distributed. This condition reinforces the validity of the regression model, as it supports the use of statistical inferences based on the assumption of normality.

Taken together, the three diagnostic analyses confirm the adequacy of the proposed regression model, demonstrating that it satisfies the classical assumptions required for reliable interpretation and application. The statistical validity observed enhances both the robustness of the estimates and the confidence in the conclusions drawn from the model.

Box 10

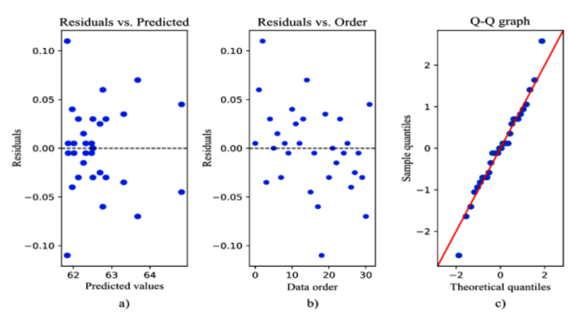


Figure 6

Diagnostic graphs of the factorial regression model: a] residuals vs. predicted values, b] residuals vs. experimental execution order and c] Q-Q graph to evaluate the normality of the residuals.

Source: own

To develop a robust prediction model for the mass of injection-molded parts, the random forest technique was employed. This method is widely applied to regression problems due to its capacity to model nonlinear relationships and capture interactions among multiple variables without relying on strict statistical assumptions.

The experimental dataset generated through the factorial design was used for training.

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The response variable corresponded to part mass, while the predictors were the four process factors: holding pressure, injection pressure, injection time, and injection speed. The dataset was partitioned into training [80%] and validation [20%] subsets, with a fixed random seed to ensure reproducibility.

The RF regression model was configured with 100 estimators and a maximum tree depth of 10. At each node, the number of features considered corresponded to the square root of the total predictors. The bootstrap option was disabled during tree construction due to the limited dataset size.

These parameter settings were selected based on practical considerations, seeking an appropriate balance between predictive accuracy and generalization capability.

Once the training phase was completed, the full data set was evaluated. Table 5 shows the mass values obtained experimentally [EXP], with the regression model [REG], and with random forests [RF] for each test.

Box 11

Table 5

Mass values obtained for each test experimentally, with the regression model and with the random forest algorithm.

Test number	Mass [m], g		
	EXP	REG	RF
1	62.48	62.475	62.475
2	62.83	62.770	62.770
3	61.95	61.840	61.840
4	63.28	63.315	63.315
5	62.16	62.130	62.160
6	62.51	62.510	62.510
7	62.28	62.265	62.250
8	62.82	62.850	62.880
9	61.87	61.865	61.870
10	62.32	62.325	62.325
11	62.01	61.970	61.970
12	62.72	62.695	62.670
13	62.02	62.015	62.010
14	62.54	62.510	62.510
15	63.75	63.680	63.680
16	64.78	64.825	64.870
17	62.47	62.475	62.475
18	62.71	62.770	62.770
19	61.73	61.840	61.840
20	63.35	63.315	63.315
21	62.10	62.130	62.160
22	62.51	62.510	62.510
23	62.25	62.265	62.250
24	62.88	62.850	62.880
25	61.86	61.865	61.870
26	62.33	62.325	62.325
27	61.93	61.970	61.970
28	62.67	62.695	62.670
29	62.01	62.015	62.010
30	62.48	62.510	62.510
31	63.61	63.680	63.680
32	64.87	64.825	64.870

Subsequently, the predictive performance of the regression model and random forests was evaluated in comparison with the experimental values, see Table 6. To do this, three statistical metrics were calculated: the mean square error [MSE], the root mean square error [RMSE] and the coefficient of determination [R²], which allow quantifying the accuracy and adjustment capacity of the models.

Box 12

Table 6

Title [Should not be images-everything must be editable]

Metrics	Regression model	Random forest
MSE	0.0018	0.0021
RMSE	0.0426	0.0460
R^2	0.9968	0.9964

Both models exhibited high predictive performance, with R^2 values approaching 1. Although the factorial regression model achieved slightly higher accuracy, the random forest approach provides additional advantages, particularly in its ability to capture nonlinear relationships and complex interactions among process variables.

Figure 7 presents a comparative analysis of the predictive capacity of both model linear regression and random forests evaluated against the experimental masses obtained in the injection molding process. The close agreement between predicted and experimental values highlights the robustness of both approaches, reinforcing their suitability for modeling the behavior of injection-molded part mass.

Box 13

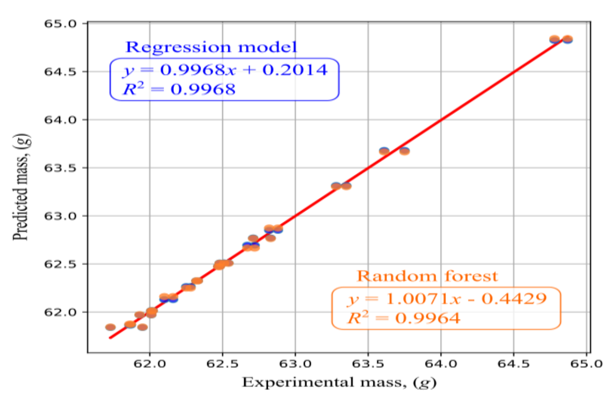

Figure 7

Comparison between linear regression and random forest models for mass prediction in injection molded parts

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Both models demonstrated high accuracy, with coefficients of determination exceeding 99.6%. The adjustment equations indicate that both algorithms adequately capture the linear relationship between the variables. However, the random forest model introduces a slight systematic overestimation in the upper range of the data, as evidenced by a slope greater than unity.

The close proximity of the predicted values to the identity line confirms that both models reproduce the experimental results with high fidelity. Nevertheless, the slightly nonlinear behavior of the random forest model may provide advantages in scenarios with greater complexity or variability, as it incorporates more flexible relationships without requiring explicit distributional assumptions.

Overall, the comparison suggests that while the linear regression model is sufficient under controlled conditions, random forests represent a more versatile and robust alternative for dynamic industrial environments, where nonlinear factors and noise can affect predictive accuracy.

Figure 9 presents a comparison between the experimental mass values and the predictions generated by both models—linear regression and random forests. The results demonstrate that both predictive approaches replicate the experimental values with high fidelity across all tests.

Box 14

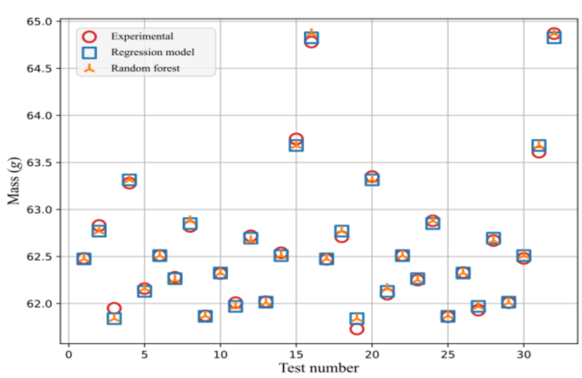

Figure 8

Comparison between experimental mass values and predictions generated by two models: linear regression and random forests.

Both the regression and random forest models exhibit a strong ability to capture the overall trend in the data without introducing significant fluctuations.

The regression model appears to align slightly more closely with the experimental values in certain regions, whereas the random forest approach may better capture nonlinear interactions in more complex scenarios or under higher levels of experimental noise. This graphical analysis complements the statistical metrics, demonstrating that predictive models not only achieve high quantitative accuracy but also provide a consistent representation of the behavior of the response variable.

Conclusions

The results obtained in this research demonstrate that it is possible to accurately model and predict the mass of injection-molded parts using both statistical approaches and machine learning algorithms.

The factorial regression model allowed us to identify the main factors influencing mass, with particular emphasis on holding pressure and the interaction between time and injection speed.

These findings were supported by analysis of variance, interaction graphs, and three-dimensional visualizations, consolidating the validity of the statistical approach.

On the other hand, the random forest algorithm showed competitive performance with respect to the regression model, achieving R^2 values greater than 0.996. Although it presented a slight overestimation in certain ranges, its ability to capture nonlinear relationships makes it a robust tool in the face of experimental variability or complex industrial scenarios.

Overall, the comparison of both approaches suggests that the regression model is suitable for controlled conditions and well-defined systems, while random forests provide additional flexibility in dynamic contexts. The combination of classical statistical methods with modern machine learning techniques offers a powerful framework for improving the understanding and optimization of injection molding processes.

Declarations

Conflict of interest

The authors declare no interest conflict.

Zavala-Gutiérrez, Jesús, Pérez-Márquez, David, Escalera-Rodríguez, Hugo, González-Hernández, José Antonio and Alcántar-Camarena, Víctor. [2025]. Analysis and prediction of the mass of injection molded parts using factorial models and random forests. Journal-Industrial Organization. 9[16]1-11: e3916111.
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Author contribution

Zavala-Gutiérrez*, Jesús*: Writing, Investigation, Formal analysis, Data curation, Methodology, Visualization.

Pérez-Márquez, David: Methodology, Software, Writing – review and editing.

Escalera-Rodríguez, Hugo: Methodology, Software, Writing – review and editing.

González-Hernández, José: Methodology, Software, Writing – review and editing.

Alcántar-Camarena, Víctor: Project administration, Methodology, Resources, Writing – review and editing.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

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Abbreviations

df	Degrees of Freedom
DoE	Design of Experiments
EXP	Experimental Data
k	Factor
mean_sq	Mean squares
MSE	Mean Square Error
P_h	Holding Pressure
P_i	Injection Pressure
R^2	Coefficient of Determination
REG	Regression model
RF	Random Forest
RMSE	Root Mean Square Error
sum_sq	Sum of squares
t_i	Injection Time
v_i	Injection Speed

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Article

Use of slow water in Rio Santiago in Nayarit, through a flow multiplier group with waterotor [G.M.C.W.] for micro electricity generation for the formation of agro parks, in the State of Nayarit.

Aprovechamiento de aguas lentas Rio Santiago en Nayarit, A través de grupo multiplicador de caudal con waterotor [G.M.C.W.] para micro generación eléctrica para formación de agro parques, en el Estado de Nayarit.

Jaime-Navarro, Agustín [a], Bonilla-Alejo, Sergio Raúl [b] and Rodríguez-Rodríguez, Joel [c]

[a] ROR Universidad Tecnológica de Nayarit 0009-0008-2054-3746 • 2025063
[b] ROR Universidad Tecnológica de Nayarit 0009-0008-3650-3810 • 396106
[c] ROR Universidad Tecnológica de Nayarit 0000-0001-9262-5312 • 568583

Classification:
Area: Engineering
Field: Microgeneration of electrical energy.
Discipline: Electric technology.
Subdiscipline: Microelectronics: iii-v and alternative technologies.

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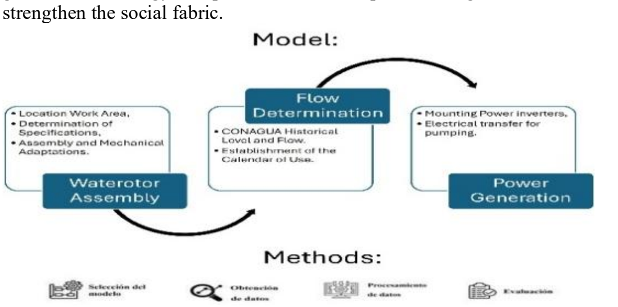
* ✉ [itcar.nayarit@gmail.com]

Abstract

The continuity of research developed, Jaime-Navarro, Agustín [2024] is presented. Integration of green technologies for the generation of electric energy using microgenerators and atmospheric batteries in the irrigation district #043 Alejandro Gascón Mercado, Canal Centenario, State of Nayarit. Journal Renewable Energy, 8[20]1-6: e50820106, 1-6.DOI: 10.35429/JRE.2024.8.20.5.6.; where the high generation potential available in the northern area of the State of Nayarit is identified, to micro generate electricity through the flow of slow water in the Santiago River through Waterotor micro generators. Improvement goals include: Affordable and local energy: diesel substitution in pumping; stabilization of electricity costs and reduction of supply interruptions; Increase in added value in agricultural products originating in the irrigation district with post-harvest processes: Cold chain, drying, milling, packaging and transformation allow better sales of rice, corn, beans, tobacco, dairy, fish and meat: Increase in income and employment: Operation of agro parks, maintenance of microturbines, cold logistics, packaging and local marketing; Increased health and quality of life: Refrigeration for vaccines and food, public lighting, connectivity and services for schools and clinics. Improving Climate Resilience: 24/7 Energy Availability from the Santiago River for pressurized irrigation, aeration in ponds, drought pumping and emergency backup; and Community governance: Energy cooperatives with surplus sharing and fair tariffs strengthen the social fabric.



Micro power generation, Santiago River, Slow water flow, Waterotor micro generators, Renewable electric energy, Affordable and local energy, Diesel substitution.

Resumen

Se presenta la continuidad investigación desarrollada, Jaime-Navarro, Agustín [2024]. Integration of green technologies for the generation of electric energy using microgenerators and atmospheric batteries in the irrigation district #043 Alejandro Gascón Mercado, Canal Centenario, State of Nayarit. Journal Renewable Energy, 8[20]1-6: e50820106, 1-6.DOI: 10.35429/JRE.2024.8.20.5.6.; donde se identifica el alto potencial de generación disponible en zona norte del Estado de Nayarit, para micro generar energía eléctrica por medio del flujo de aguas lentas en el Rio Santiago a través de micro generadores Waterotor. Los objetivos de mejora incluyen: Energía asequible y local: sustitución diésel en bombeo; estabilización costos de energía eléctrica y reducción de interrupciones por suministro; Incremento de valor agregado en productos agrícolas con origen en el distrito de riego con procesos postcosecha: Cadena de frío, secado, molienda, empaque y transformación permiten vender mejor arroz, maíz, frijol, tabaco, lácteos, pescado y cárnicos: Aumento del Ingreso y empleo: Operación de agro parques, mantenimiento de microturbinas, logística de frío, empaques y comercialización local; Incremento de Salud y calidad de vida: Refrigeración para vacunas y alimentos, alumbrado público, conectividad y servicios para escuelas y clínicas. La mejora de la Resiliencia climática: Disponibilidad de Energía 24/7 del Río Santiago para riego presurizado, aireación en estanques, bombeo contra sequías y respaldo en emergencias; y Gobernanza comunitaria: Cooperativas energéticas con reparto de excedentes y tarifas justas fortalecen el tejido social.

Micro generación de energía, Río Santiago, Flujo de aguas lentas, Micro generadores Waterotor, Energía eléctrica renovable, Energía asequible y local, Sustitución de diésel.

Area: Advocacy and attention to national problems

Citation: Jaime-Navarro, Agustín, Bonilla-Alejo, Sergio Raúl and Rodríguez-Rodríguez, Joel. [2025]. Use of slow water in Rio Santiago in Nayarit, through a flow multiplier group with waterotor [G.M.C.W.] for micro electricity generation for the formation of agro parks, in the State of Nayarit. Journal-Industrial Organization. 9[16]1-7: e4916107.

Introduction

Our country, like the rest of the world, is experiencing an ever-increasing demand for electrical energy. In addition, it must direct its efforts towards an energy transition with a focus on the use of renewable and sustainable non-polluting energy sources available in its territory. These should not contribute to harming the environment, the soil, the water or the ozone layer, reducing the carbon footprint of various human activities. Currently, developed countries are determining the trends in the increase in demand for electrical energy, caused by the rise in the use of electrical energy in:

a] So-called human electric mobility, through electric trains, hybrid buses and electric cars.

b] The increase in the development of semiconductor technologies and the use of artificial intelligence, which demands ever-greater amounts of electrical energy.

c] The future urgency of all nations to use water desalination plants for agricultural irrigation and human consumption [which require large amounts of electricity, increasing the percentage of so-called food security].

These are the three main causes driving the increase in electricity demand in first world countries.

Mexico, and specifically the state of Nayarit, must not remain on the sidelines of technological development to meet these needs. Nayarit must not ignore and lag behind the technological advances that are taking place around the world.

It is considered alarming that the water stress caused by climate change in our country and state has been reflected in the last five years. For this reason, it is necessary to set objectives focused on finding the best ways and means to take advantage of the resources currently available in our regions to generate or micro-generate electricity.

This becomes a matter of prime importance, as it involves desalinating seawater for human consumption and agricultural irrigation, as well as for livestock, agriculture and livestock consumption. This project could even contribute to increasing food security in our country.

The areas along the Santiago River in Nayarit where it is proposed to install Waterotor micro-generators are located along several kilometres of the irrigation zone, starting in the municipality of Santiago Nayarit between the diversion dams operated by the C.F.E. and the 'Amado Nervo' diversion dam in the community of Jileño Nayarit operated by CONAGUA.

Nayarit has the hydraulic potential for micro-generating electricity, with a minimum depth of 1.5 metres that allows for the efficient operation of a Waterotor micro-generator. These conditions are naturally generated by the Santiago River in Nayarit.

The Federal Government is responsible for the implementation of Irrigation District #043 Alejandro Gascón Mercado. This situation requires an increase in the flow contribution [56 m3 + 60 m3] by the three existing hydroelectric dams in the states of Jalisco-Nayarit, operated by the C.F.E.

Methodology

Taking as a starting point the study report based on samples taken by the National Water Commission at a monitoring and sampling point in CAPOMAL, under the responsibility of CONAGUA's technical sub-directorate for groundwater management, which was published in 2024. Entitled 'Update on the average annual water availability in the Santiago-San Blas aquifer [1803]' Below is an overview of the general location of the aquifer on which the study was based.

Box 1

Figure 1

Location of the aquifer.

Reports are available for all sampling, carried out at the sampling point at CAPOMAL. A bar graph with the results of the flow values in cubic metres per second can be seen below.

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It can be seen that there are real possibilities for micro-generation with this mechanical force.

Box 2

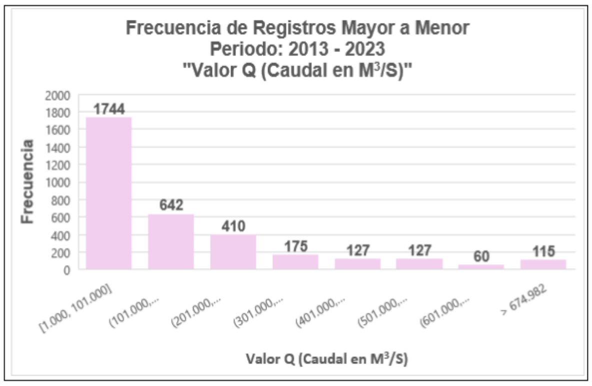

Figure 2
Flow values in cubic metres per second from 2013 to 2023.

Figure 2 shows the flow rates measured over a 10-year period up to 2023. Based on these recorded flow values, locations with depths greater than 1.5 metres can be found. It is entirely feasible and highly advantageous to use Waterotor micro-generators, without the need to build dams and with minimal civil engineering investment. No fuel is used and preventive maintenance costs for micro generators are low. These micro generators produce renewable and sustainable energy.

It should be noted that the micro generator produces direct current in a sufficient range, which is rectified and synchronised, as well as regulated to alternating current, at 220 V three-phase at 60 Hz.

The above is the important function of an INVERTER-REGULATOR. It not only converts electrical energy from DC to AC, but also synchronises it at 60 Hz and maintains a constant supply of 220 V three-phase electrical energy.

This research article proposes the design of a prototype adapted to the waterotor. This device is intended to take advantage of the slow water flow and guarantee the calculated speeds required by the micro generator to generate up to 1 MW.

It is based on the mathematical principle of the following well-known formula.
The formula for converting flow rate to average speed.

$$v = \frac{Q}{A}$$

Equation 1
Where:
v= Average velocity in m/sec.
Q= Flow rate in cubic metres.
A= Area in square metres.

To convert flow [Q] to mean velocity [v] to be required and [A] is the wetted area of the river section in which the device integrated with the waterotor will be immersed.

The following is an illustration of the design proposal that was elaborated and named HYDRAULIC FLOW VELOCITY MULTIPLIER of the device already integrated with the waterotor.

Box 3

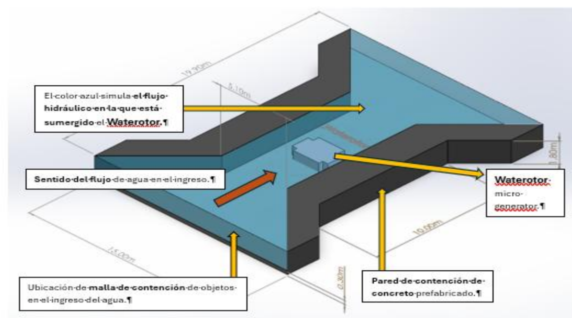

Figure 3
The proposed design of the hydraulic flow rate multiplier, integrated with waterotor, is illustrated.

Therefore, with the proposed design to be implemented as a single integrated block, that is, as a WATEROTOR AND HYDRAULIC FLOW SPEED MULTIPLIER GROUP, it will be possible to obtain 1 MW with a minimum investment of money in any section of the Santiago River in Nayarit. The same or less for each waterotor micro-generator with flow speed multiplier. Many kilometres of river from the C.F.E. diversion dams to before the Jileño dam in Nayarit.

It can be deduced that if it is a river with slow-moving water and good flow, and that flow is present 365 days a year, then it has everything necessary for continuous micro-generation of electrical energy. Electricity at 440 V or 220 V, three-phase at 60 Hz. Many WATEROTOR FLOW MULTIPLIER GROUP UNITS *[G.M.C.W.]* can be installed.

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Jaime-Navarro, Agustín, Bonilla-Alejo, Sergio Raúl and Rodríguez-Rodríguez, Joel. [2025]. Use of slow water in Rio Santiago in Nayarit, through a flow multiplier group with waterotor [G.M.C.W.] for micro electricity generation for the formation of agro parks, in the State of Nayarit. Journal-Industrial Organization. 9[16]1-7: e4916107.
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This is the hypothesis on which the research in this particular article is based. The Waterotor micro generator handles the following ranges as standard: 1 kW, 10 kW and 1 MW; only the nominal mechanical power conditions of 0.97 m/s to [≈ 1.78 m/s] are required. And minimum depths of 1.5 metres. For this micro generator to operate efficiently. In Fig. 4, below.

Box 4

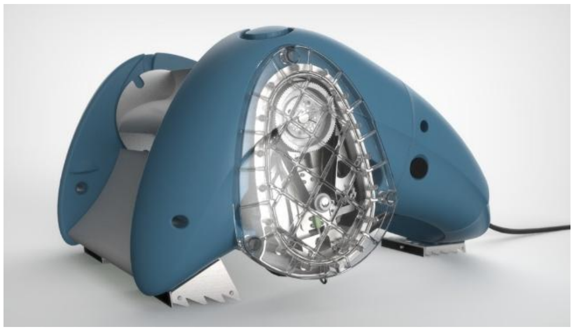

Figure 4
Waterotor Micro generator for slow water flow.

On the other hand, a descriptive block diagram is illustrated in Fig. 5 below, which tries to explain in summary form the contribution of 80 pages of historical records provided by the Comisión Nacional del Agua Nayarit [CONAGUA]. Source: CONAGUA Nayarit Oficio: B00.917.00.0.3.-027 dated 01/July/2025.

Box 5

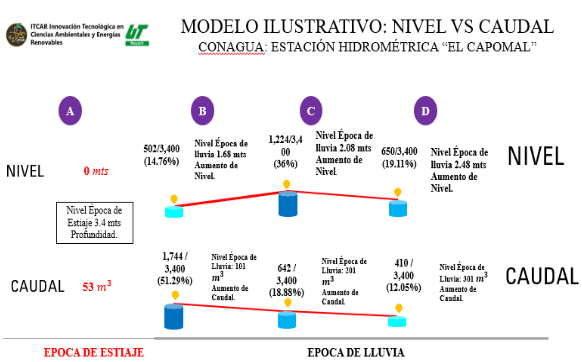

Figure 5
Illustrative model of: Level vs. Flow.
Source: CONAGUA Nayarit Oficio: B00.917.00.0.3.-027 dated 01/July/2025, information on the measurements taken in the section: El Jileño - Yago Nayarit, Period: 2013-2023, hydrometric station "El Capomal", consisting of 3,400 individual records where levels and flows are identified..

The data was obtained during the period 2013-2023 at a hydrometric station of the National Water Commission [CONAGUA], located in the town of Capomal, Nayarit.

In Fig. 5, the values for the low-flow season, in terms of level versus flow in m^3, can be seen at the bottom. It is important to mention that the flow rate during the low-flow season is less than 53 m^3/sec. This changes during the rainy season.

Those 53 m^3/sec. is the water expenditure established by C.F.E. and CONAGUA, which allocates and distributes it for ecological services, for the annual water supply from C.F.E. diversion dams. The illustration also shows the average water level, which rises 1.68 metres Plus the 3.4 metres average depth over many kilometres, before the water reaches Jileño, to the mouth of the river.

This condition changes during the five months of the year in the rainy season, when an increase of 5.08 metres can be seen. This is in the same place where sampling was carried out during the dry season. In other words, the increase in the maximum recorded water level was 2.48 metres. However, this only occurs during the five months of rainfall.

This data is extremely important to take into account when installing Waterotor micro-generators along these areas of the river [areas with high potential for micro-generation of electrical energy].

With the current flow and water level values, it is possible to install several Waterotor micro-generators in the Santiago River area before the small Jileño dam.

Next, the formula for a rectangular surface was applied as an example. The flow value of *Q=53 m^3/seg.*

$$v = \frac{53}{\text{ancho} \times \text{profundidad}} \; (\text{m/s})$$

Formula 2

To calculate the average velocity on a rectangular surface. And substituting the area values in m^2 A= 6.X5m.=30 m^2
Substituting:

Jaime-Navarro, Agustín, Bonilla-Alejo, Sergio Raúl and Rodríguez-Rodríguez, Joel. [2025]. Use of slow water in Rio Santiago in Nayarit, through a flow multiplier group with waterotor [G.M.C.W.] for micro electricity generation for the formation of agro parks, in the State of Nayarit. Journal-Industrial Organization. 9[16]1-7: e4916107.
https://doi.org/10.35429/JIO.2025.9.16.4.1.7

Results:

v* = 1.76 *m/seg. *An excellent average speed value for a micro-wattspeed generator. It exceeds almost twice as much as 0.97 m/sec. minimum. Could aim for 1 MW/Hr.*

ContinIn line with the previous comments. This investigation points out that, in a meeting held with authorities from the National Water Commission Delegation in Nayarit,it was revealed to us, without specifying the quantities, that as a result of the commissioning of Irrigation District No. 043 Alejandro Gascón Mercado [Canal Centenario], which has already been authorised, the increase in water consumption will more than double the average flow rate annually.

The amount of water flow in areas with high flow potential for installing micro-generators on the Santiago River there are many kilometres from the last C.F.E. diversion dam to the small Jileño dam. It is theoretically possible to find 20 or more locations to generate a minimum of 20 MW, 365 days a year, 24 hours a day, with low monetary investments compared to a hydroelectric dam.

Box 6


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Lugar: Tepic, Nayarit
Fecha: 01 de julio del 2025
Oficio No: Numero B00.917.00.0.3.-027
00782

Dirección Local Nayarit
Subdirección Técnica
Centro de Previsión Meteorológica

Asunto: Solicitud de información.

M. C. A. Sergio Raúl Bonilla Alejo
Investigador Responsable del Proyecto PRIMSO 025
M.A. Agustín Jaime Navarro
Investigador Responsable Técnico Proyecto PRIMSO 025
Presente

En atención a oficio con fecha del 23 de junio del año en curso en donde solicita información de aportación de los caudales históricos de los últimos 10 años del cauce del Rio Santiago en el tramo de las localides El Jileño-Yago Nayarit para el desarrollo de el Proyecto "PRIMSO-025: Caracterización hidráulica para implementar Micro generación Eléctrica a partir del aprovechamiento del cauce del distrito de riego #043 Alejandro Gascón Mercado.

Envío al correo raul.bonilla@utnay.edu.mx información de los gastos de la estación hidrométrica de "El Caporal" ubicada en la localidad de El Caporal, Nayarit, del periodo 2013-2023, siendo hasta este año con la información que cuenta la CONAGUA.

Sin más por el momento reciba un cordial saludo.

ATENTAMENTE

Ing. Gerardo Leyva Alvarez
Director Local

Revisó	Ing. Hugo Arturo Segura Barqueño, Subdirector Técnico	Firma
Elaboró	C. Gaddi Neftalí Rodríguez Sanagón, Técnico Especializado	Firma

Figure 6

Evidence of evidence of meeting in July 2025 with the National Water Commission.

This amount of electrical energy could be used to create attractive conditions for domestic and foreign investors to set up productive industrial units that could add value to crops grown on arable land along the Santiago River.

Through <u>*agro parks*</u>, which generate a prevailing way of life for the application of a first-rate linear and sustainable economic model.

Thus, with the implementation of this project, we would contribute to increasing food security in our country and providing an economic and employment boost for the Santiago Ixcuintla and Nayarit region in general.

Furthermore, this project could be *replicated* in many states of the Mexican Republic and even be part of the *Mexico Plan of the Federal Government.*

It is worth mentioning that, at the global level, the UN, through the world's governments, with the 2030 Agenda and the 17 Sustainable Development Goals, is seeking to change the way electricity is generated and consumed, the impact of the transition of productive industries that use renewable energies, and the shift from petrol cars to hybrid and/or electric cars to establish new ways of promoting human mobility.

The rest of human activities involve other changes in human electricity consumption. With this frame of reference, the present research developed by members of the multidisciplinary academic body of the Technological University of Nayarit[1] ITCAR[2] [Technological Innovation in Environmental Sciences and Renewable Energies] is identified.

The above, during the period 2022-2025, is a formal research project that has taken as its starting point the chapter entitled: 'Characterisation of Potential Clean Energy Generators in the State of Nayarit, to develop the 2020-2050 Energy Transition Matrix'[3].

This research is aimed at the micro-generation of renewable and sustainable energy. It focuses on the exploitation of slow water flows: streams, rivers and canals. Mexico, and especially the Nayarit region, has a large capacity of usable hydrological resources, with rivers that flow 365 days a year.

The WATEROTOR micro generator operates efficiently at water speeds as low as 3.2 km/h [0.9 m/s], ideal for installation in areas with high potential identified in the Santiago River [from the C.F.E. hydroelectric plants and before the Jileño dam] in the state of Nayarit.

Below is an image of the selected micro generator. WATEROTOR is completely submersible, i.e. it is submerged in water, easy to install and uninstall, and fully mobile.

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[1] UTNAY website: https://www.utnay.edu.mx
[2] ITCAR Facebook page: https://www.facebook.com/ITCARUTN
[3] Repository of the National Congress of Academic Bodies, Research and Postgraduate Studies, Technological and Polytechnic Universities ISBN: 978-607-96023-1-4: E-book - CNCAIyP - Google Drive http://https://drive.google.com/drive/folders/1rn358lZF1mWsJVUFP4mLZfCd94jkKQjk?fbclid=IwY2xjawFal_pleHRuA2FlbQIxMAABHVQfVHXqpKLRh0Ok8_z0scpHLf8OkX3FCLVjp0azwSUBUkm15wAUpRXJgg_aem_FE3tkrGklMIXI6h8_nEZWw..

Box 7

Figure 7
Submersion manoeuvres of small watercraft.

The waters of the Santiago River, where it is proposed to submerge several Waterotor micro-generators, are murky and, due to the force of the current, carry stones, pieces of branches, and sometimes regional fauna, etc.

For this reason, each micro-generator will require a net to divert objects at each water inlet of each micro-generator.

The technical specifications for Waterotor are listed below:

Detailed technical specifications and operating and installation conditions:

Minimum depth required: 1.12 m [3.7 ft]. Up to 1.5 m.

Operating temperature: +1 °C to +50 °C.

Medium: Fresh or salt water [rotomoulded plastics and stainless steel]. These are the materials used to manufacture most of the components that make up the Waterotor Micro Generator.

Output data on electricity generation

Rectification/inversion options: the system can include electronic controllers for regulated DC output when used with batteries or microgrids. $0.94 Mexican pesos. Less than 1 peso per KW/Hr.

The following table summarises the technical characteristics of the Waterotor Micro generator. Source of the values in the specifications table: manufacturer's website.

Category	Specification
Technology	Patented hydro-kinetic rotor generator [combines lift + drag]].
Minimum water velocity	0.9 m/s [≈ 3.2 km/h].
Optimum speed	2–2.5 m/s [≈ 7–9 km/h].
Maximum speed	Up to 4 m/s [≈ 14.4 km/h].
Minimum depth	1.12 m [3.7 ft]. A 1.5 m.
Temperature range	+1 °C a +50 °C.
Ambient	Fresh or salt water [materials: broken moulded plastic + stainless steel]].
Efficiency	50–60 % of the available kinetic energy.
Rated power	Models: 1 kW, 10 kW y 1 MW.
Electrical output	120 V / 240 V AC [50/60 Hz]. Optional: DC regulated for batteries/micro-grids.
Generation cost	≈ 0.05 USD/kWh [in optimal flow]. $0.94 Cents
Durability [MTBF]	1 kW: 10–15 years. 10 kW – 1 MW: 20+ years.
Maintenance	Minimum: cleaning of debris and overhaul of bearings every 3-5 years.
Installation time	4 a 8 hours .
Personnel requirement	2–3 people .
Transport	Portable, fits in a pickup truck. Up to 20 units in ISO container.
Environmental impact	Zero emissions. Does not harm fish or seabed. Can reduce local erosion.
Applications	Isolated rural communities, islands, offshore platforms, diesel replacement, disaster response, military use.

In order to take advantage of the flow during the dry season [53 cubic metres per second] or during periods of rain and precipitation, the Solid Works platform was used to design the proposed generator.

It should be noted that if this project is carried out on the Santiago Nayarit River, it would set a precedent for other states in Mexico that have several rivers with flows 365 days a year and depths better than those in Nayarit and this research, which occur naturally and even exceed those in Nayarit.

Box 8

Figure 8

Agro parks with crops of importance to Mexico's food security.

References

- **Official website** Waterotor Energy Technologies | Renewable Energy Solutions

Official website ITCAR Innovación Tecnológica en Ciencias Ambientales y Energías Renovables | Facebook

- Image of the Document: 1st Part Water infrastructure in Mexico. IMTA [MEXICAN INSTITUTE OF WATER TECHNOLOGY].

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Electromobility in Mexico: Gaps and Opportunities in Public Policies for Electric Vehicles

Electromovilidad en México: Brechas y Oportunidades en Políticas Públicas para Vehículos Eléctricos

Salgado-Conrado, Lizbeth [a], Pérez-García, Laura Andrea * [b] and Álvarez-Macías, Carlos [c]

[a] ROR Universidad Autónoma de Coahuila • AGT-8696-2022 • 0000-0002-2181-5861 • 296620
[b] ROR Tecnológico Nacional de México/Instituto Tecnológico de La Laguna • HPF-4026-2023 • 0000-0002-5880-6192 • 887623
[c] ROR Tecnológico Nacional de México/Instituto Tecnológico de La Laguna H-3977-2017 • 0000-0002-2263-0316 • 165872

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* ✉ [laperezg@lalaguna.tecnm.mx]

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Abstract

The electrification of transportation is central to Mexico's climate and sustainability goals. This article analyzes the current state of public policies for electric vehicles [EVs], focusing on the National Electric Mobility Strategy [ENME] and supporting fiscal, regulatory, and infrastructure measures. Through a comparative review of Latin American leaders—Colombia, Chile, and Costa Rica—the study identifies effective policy tools that have accelerated EV adoption and charging infrastructure, and advanced integration with renewable energy. Using a prioritization framework based on technical-economic feasibility, emissions reduction potential, and alignment with global goals [Paris Agreement], the article offers tailored, evidence-based policy recommendations. A SWOT analysis reveals Mexico's progress and remaining challenges, including limited coordination and uneven infrastructure. Findings show that while Mexico has a solid strategic foundation, it must expand incentives, improve institutional alignment, and ensure equitable access to infrastructure in order to meet its decarbonization targets and become a regional benchmark in sustainable mobility.

Electromobility in Mexico: Gaps and Opportunities in Public Policies for Electric Vehicles		
Objectives	Methodology	Contribution
To evaluate and strengthen public policies for electric vehicles in Mexico through comparative analysis and evidence-based recommendations.	Comparative case analysis combined with SWOT assessment and feasibility evaluation.	Proporcionar un marco basado en evidencia para identificar brechas de políticas y oportunidades para acelerar la adopción de vehículos eléctricos en México.

Policy Gaps, Latin American Benchmarking, Sustainable

Resumen

La electrificación del transporte es clave para alcanzar los objetivos climáticos y de sostenibilidad de México. Este artículo analiza el estado actual de las políticas públicas para vehículos eléctricos [VE], con énfasis en la Estrategia Nacional de Movilidad Eléctrica [ENME] y los instrumentos fiscales, regulatorios y de infraestructura que la acompañan. A través de una comparación con casos exitosos en América Latina —como Colombia, Chile y Costa Rica— se identifican herramientas de política efectivas para acelerar la adopción de VE, ampliar la infraestructura de carga e integrar la movilidad con energías renovables. Mediante un marco de priorización basado en la viabilidad técnico-económica, el potencial de reducción de emisiones y la alineación con agendas globales [Acuerdo de París], se proponen recomendaciones de política sustentadas en evidencia. Un análisis FODA revela avances, brechas y oportunidades. Los resultados destacan que México debe fortalecer la coordinación institucional y ampliar los incentivos para consolidarse como líder regional en movilidad sostenible.

Electromovilidad en México: Brechas y Oportunidades en Políticas Públicas para Vehículos Eléctricos		
Objetivos	Methodología	Contribución
Evaluar y fortalecer las políticas públicas para vehículos eléctricos en México mediante análisis comparativo y recomendaciones basadas en evidencia.	Análisis de casos comparativo combinado con evaluación FODA y evaluación de viabilidad.	Proporcionar un marco basado en evidencia para identificar brechas de políticas y oportunidades para acelerar la adopción de vehículos eléctricos en México.

Brechas en las políticas, Comparación de referencia con América Latina, sostenible

Area: Advocacy and attention to national problems

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Introduction

The transition toward electric mobility is a key component of global strategies to mitigate climate change, particularly in the transportation sector, which accounts for 24% of global energy-related CO_2 emissions [Kumar, 2024]. In this context, electric vehicles [EVs] have emerged as a crucial technological solution, demonstrating reductions of up to 50–70% in greenhouse gas [GHG] emissions compared to conventional vehicles, considering the current energy mix [Ghosh, 2020, Bai & Liu, 2021]. However, in emerging economies such as Mexico, the mass adoption of EVs faces complex challenges involving economic, regulatory, and infrastructure-related factors [Zafar, 2023].

From a technical perspective, the effectiveness of public policies aimed at promoting electromobility critically depends on three interrelated components: [1] fiscal schemes that reduce the initial cost gap, [2] accelerated deployment of charging infrastructure, and [3] integration with renewable energy systems [IEA, 2021]. Recent data show that while leading countries such as Norway have achieved EV market shares as high as 86% [Carranza, et al., 2013], Mexico accounts for only 2.8% of the total automotive market [Oxford Analytica, 2021], despite being the seventh-largest automobile producer in the world [International Trade Administration, 2023].

The core of the issue lies in the significant disparity between the public policy instruments implemented in Mexico and those required to meet its climate commitments. The PRODESEN 2022–2036 outlines the need for 1.3 million EVs in circulation by 2030, a goal that requires annual growth rates of 32% [SENER, 2021]. However, the current regulatory framework presents critical limitations: fragmented fiscal incentives [only 9 out of 32 states offer exemptions], insufficient infrastructure [2.4 chargers per 100,000 inhabitants versus 35 in the U.S., according to BNEF, 2023], and the absence of sales mandates such as the Zero Emission Vehicle [ZEV] standards adopted in California [Salgado-Conrado, et al., 2024].

Therefore, the objective of this article is to critically analyze the public policy architecture for electromobility in Mexico by:

- Quantitatively evaluating the real impact of existing incentives on the Total Cost of Ownership [TCO]
- Developing a comparative model with successful international cases [Brazil, Colombia, and Costa Rica]
- Identifying regulatory gaps and proposing policy recommendations based on empirical evidence

The academic contribution is structured across three dimensions: [a] development of an analytical framework adapted to emerging economies, [b] quantification of price-demand elasticity for EVs in the Mexican context, and [c] integration of geographic variables into the analysis of policy effectiveness.

This chapter analyzes the current status and public policies related to electric vehicles [EVs] in Mexico. It begins with an introduction to the national context and the study's objectives, followed by a methodology based on comparative analysis, feasibility evaluation, and SWOT assessment. The chapter explores the EV market, charging infrastructure, and existing fiscal incentives. It also outlines recent institutional and regulatory progress, as well as the main gaps in public policy. Through a comparison with leading Latin American countries [Colombia, Chile, and Costa Rica], the study identifies best practices and areas for improvement. Finally, it presents evidence-based strategic recommendations to strengthen electromobility in Mexico, focusing on infrastructure expansion, incentive design, institutional coordination, and integration with renewable energy sources.

Methodology

This study employs a mixed-methods approach, combining qualitative and quantitative analysis to examine public policies on electromobility in Mexico. The research methodology comprises three key components: First, systematic data collection from primary sources [including analysis of regulatory frameworks] and secondary sources [such as EV sales statistics from AMIA and INEGI, and charging infrastructure data from the Mexican Electric Mobility Association]. Second, a comparative policy analysis benchmarking Mexico's progress against successful Latin American cases [Colombia, Chile, Costa Rica], evaluating effectiveness in technology adoption and infrastructure deployment through SWOT analysis.

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Third, evidence-based policy recommendations developed through feasibility assessments [technical-economic criteria] and alignment with global sustainability goals [Paris Agreement, SDGs]. While the study acknowledges limitations like uneven regional data availability, its methodology provides a transferable analytical framework for other emerging markets facing similar energy transition challenges.

Current Status of Electric Vehicles in Mexico

Market and Adoption

In Mexico, the adoption of electrified vehicles has shown an interesting yet still modest evolution within the context of the overall automotive market. Sales data from 2016 to June 2025 reveal significant patterns in the penetration of these technologies [AMIA, 2023]. During this period, a total of 202,562 units of electrified vehicles were sold, representing 2.5% of the total light vehicle sales in the country [9,414,028 units]. However, when considering only fully electric vehicles [EVs], these accounted for 4.1% of total light vehicle sales [INEGI, 2025].

The annual analysis shows a growing trend in the adoption of these technologies, although with clear differences among vehicle types: hybrid electric vehicles [HEVs], plug-in hybrid electric vehicles [PHEVs], and battery electric vehicles [EVs]. Throughout this decade, there is notable growth in the total number of units sold, especially from 2020 onwards, with a significant peak in 2024 and an apparent decline in 2025, as shown in Figure 1.

Box 1

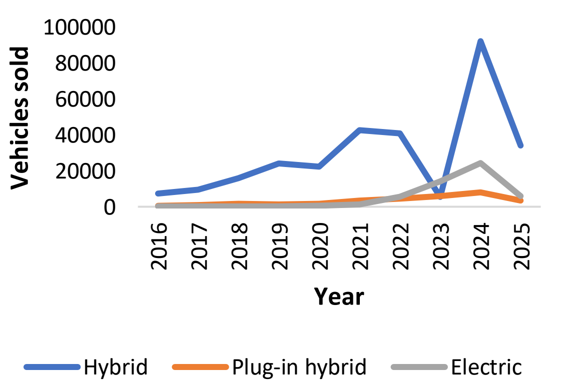

Figure 1
Sales of HEV, PHEV and EV vehicles
Own elaboration

Hybrid electric vehicles [HEVs] have consistently led the market since 2016, starting with 7,490 units sold and reaching a maximum of 92,026 units in 2024. This cumulative growth indicates that HEVs have been the most accessible and accepted technology among Mexican consumers. In 2025, 34,150 units were registered up to June, which does not necessarily represent a definitive decline. This difference compared to the previous year may simply be due to incomplete annual data. It is likely that in the second half of the year, figures will increase significantly depending on economic context and market strategies. For PHEVs, growth has been more moderate. Sales rose from 521 units in 2016 to 7,994 units in 2024, with 3,364 units counted up to June 2025. Although PHEVs offer benefits such as extended range and versatility, their adoption has been slower. This can be attributed to their higher cost compared to HEVs, as well as still insufficient charging infrastructure in many regions of the country [Salgado-Conrado, 2025]. The evolution of annual figures will also depend on second-semester market performance.

Battery EVs, on the other hand, show the fastest growth curve. From nearly symbolic figures in 2016 [254 units], they reached a peak in 2024 with 24,283 units sold. This behavior reflects growing interest in fully clean mobility solutions, likely driven by increased model availability, technological advances, government incentives, and rising environmental awareness. For 2025, 6,017 units have been registered up to June, which may also increase toward the end of the year if market conditions remain favorable.

Between 2020 and 2021, a clear inflection point is observed, with substantial increases in sales across all categories, possibly related to economic recovery after the pandemic and the boost of public policies for sustainable mobility. The year 2024 represents the sales peak for all technologies, possibly reflecting a period of strong incentives or consumer confidence. Among the best-selling electric vehicle models are the Chevrolet Equinox EV, Ford Mustang Mach-E, Chevrolet Blazer EV, Wagoneer S, and Nissan Kicks E-Power, with prices ranging from approximately MXN 299,300 for more affordable models like the SEV E-Wan Cross to over MXN 1,200,000 for luxury vehicles such as the Volvo EX30 [Latam Mobility, 2024].

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Hybrid vehicles continue to dominate the eco-friendly segment, led by popular and efficient models like the Toyota Prius, Honda CR-V Hybrid, and Ford Escape Hybrid [Nexu, 2025]. While these prices are generally higher compared to equivalent internal combustion engine [ICE] vehicles, reflecting the current cost premium of electric and hybrid technologies, this growth demonstrates increasing environmental awareness and a market trend toward democratizing electric mobility. However, challenges remain, including the need for expanded charging infrastructure and the high acquisition costs, even as the government promotes policies aimed at fostering the adoption of clean transportation technologies.

The consumer profile for EVs in Mexico varies notably between corporate and individual buyers. On the corporate side, businesses and fleet operators have been early adopters of electrified vehicles, attracted by potential cost savings in fuel and maintenance, as well as corporate social responsibility commitments and regulatory incentives [Ernst & Young México, 2023]. Companies in sectors such as logistics, delivery, and government fleets have incorporated hybrid and electric models to reduce operating expenses and enhance their environmental credentials. Conversely, individual consumers tend to be urban residents with higher income levels and environmental awareness, often motivated by the desire to reduce their carbon footprint and benefit from emerging government incentives [AMIA, 2023]. However, high upfront costs, limited model availability, and insufficient charging infrastructure continue to restrict broader adoption among private buyers. This divergence in consumer profiles highlights the need for tailored policies and market strategies to support both segments and accelerate the overall transition to electromobility.

Charging Infrastructure

Despite recent growth in electromobility, Mexico's EV charging infrastructure remains unevenly distributed, with a strong concentration in densely populated and high-income urban areas. Leading the network are Mexico City, Jalisco, and Nuevo León, where the majority of EV registrations are concentrated [Salgado-Conrado, 2025], as shown in Table 1. This highlights a significant urban–rural gap, as many peripheral and rural areas still lack adequate access to charging infrastructure.

Box 2

Table 1

Mexican charging station by state in 2020.

State	Charging Stations	Chargers	State	Charging Stations	Chargers
Aguascalientes	15	26	Nayarit	5	11
Baja California	45	115	Nuevo León	99	234
Baja California Sur	20	54	Oaxaca	11	15
Campeche	5	12	Puebla	37	86
Chiapas	11	27	Querétaro	37	106
Chihuahua	21	43	Quintana Roo	28	69
Mexico City	222	420	San Luis Potosí	13	30
Coahuila	28	63	Sinaloa	12	29
Colima	12	32	Sonora	12	29
Durango	7	13	Tabasco	4	6
Guanajuato	39	102	Tamaulipas	15	25
Guerrero	18	45	Tlaxcala	2	4
Hidalgo	9	15	Veracruz	33	73
Jalisco	103	211	Yucatán	15	44
Mexico State	80	170	Zacatecas	6	14
Michoacan	20	36			

Enerlink. [2024].

To address this disparity, expansion efforts have focused on strategic states such as the State of Mexico, Puebla, Quintana Roo, and Guanajuato, prioritizing major highways, high-traffic urban centers, and key logistical zones [Enerlink. 2024]. Currently, around 30% of charging stations are located along Mexico's main EV corridors, including the route that connects Mexico City, Querétaro, Guadalajara, and Puebla. This corridor features one of the world's fastest charging stations, located in San Lorenzo Almecatla, Puebla, with a 1 MW capacity, particularly suitable for commercial and heavy-duty vehicles [Ángel, 2023].

Another essential corridor links Coahuila, Monterrey, and McAllen, Texas, forming a strategic path for cross-border trade and tourism [Parlamento, 2017]. Infrastructure development in this northern region supports the electrification of commercial fleets and international travel, further encouraging EV adoption in one of Mexico's most economically active zones.

In addition to public efforts, private sector initiatives are playing a key role in expanding the charging network. Tesla has installed several Supercharger stations across Mexico, strategically located along long-distance travel routes and urban hubs, providing high-speed charging for Tesla users and setting a benchmark for infrastructure quality. Likewise, Iberdrola México, in collaboration with government and industry stakeholders, has launched projects aimed at installing public charging stations in commercial centers, universities, and corporate parks, focusing on accessible, open-use infrastructure for all EV brands [Latam Mobility, 2025, Iberdrola, 2025].

EV adoption in Mexico is also closely tied to demographic and economic factors. Mexico City, home to over 9 million residents and with an average monthly household income of approximately MXN 16,000, leads national EV sales with 29.2% of total registrations. It is followed by the State of Mexico [14.6%], Jalisco [9.2%], Nuevo León [8.2%], and Puebla, Guanajuato, and Michoacán, each accounting for around 3% [ENIGH, 2022].

These demonstrate how economic strength and population density significantly influence the development and location of charging infrastructure. States with stronger economies not only register more EVs but also attract greater public and private investment in charging stations, accelerating Mexico's transition toward sustainable mobility.

Public Policies for EVs in Mexico

The ENME is part of Mexico's National Development Plan 2019–2024 and has been developed by SEMARNAT with interinstitutional support from agencies such as INECC, SENER, SRE, and CONUEE. It responds to international commitments [Paris Agreement, Glasgow Pact, COP24–27] and aligns with Mexico's Special Program on Climate Change 2021–2024 [Gobierno de México, 2023].

The ENME lays out the technical, institutional, legal, financial, and incentive-based framework to promote a national transition toward electric mobility, prioritizing emission reductions, social equity, and inclusive access.Based on projections by INECC, the ENME defines three main planning horizons [Sánchez Devanny, 2023]:

2030 Targets

- 50% of new sales for light and heavy-duty vehicles will be electric or plug-in hybrids.
- Introduction of around 7 million light vehicles and 338,000 heavy-duty or passenger vehicles.
- Electrification of public transport in the 10 cities with the highest GHG and short-lived climate pollutant emissions.
- Development of a national public EV charging network, both in cities and along main highways.
- Establishment of regulations for charger homologation and approval.

2040 Targets

- 100% of new sales for light and heavy-duty passenger vehicles will be electric or plug-in hybrids.
- At least 22 million electric light vehicles and 894,000 heavy-duty or passenger vehicles in circulation.
- Nationwide system of open and homologated EV chargers in the 10 largest cities.
- A similar system across all federal highways.

2050 Targets

- 100% of new vehicle sales will continue to be electric or plug-in hybrids.
- Deployment of 31 million light electric vehicles and 987,000 heavy-duty vehicles.
- Consolidation of a national electric road system for freight and long-haul vehicles on strategic highways.

Incentives

The promotion of electromobility in Mexico depends significantly on the implementation of strong fiscal and economic incentives that encourage the adoption of EVs.

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These incentives not only aim to make EVs more affordable and attractive for consumers but also support the development of charging infrastructure, technological innovation, and domestic manufacturing capacity. The Mexican government has incorporated these incentives into various legal frameworks, particularly the Income Tax Law [ISR], Value-Added Tax Law [VAT or IVA], the Federal Tax Code, and the New Automobile Tax Law [ISAN].

Under the Income Tax Law, individuals and companies can deduct up to MX$250,000 of the purchase price of a new electric or plug-in hybrid vehicle. This cap is higher than the one applied to combustion-engine vehicles, which is typically around MX$175,000. Furthermore, businesses that lease EVs can deduct up to MX$285 per day, compared to MX$200 per day for internal combustion vehicles. In addition, investments in charging infrastructure are eligible for a 30% tax deduction, encouraging the expansion of public and private charging networks across the country [AMIA, 2022].

Another major incentive lies in the Value-Added Tax Law. EVs are exempt from VAT on both imports and domestic sales, which represents a significant reduction in upfront costs. Also, the Federal Electricity Commission [CFE] offers a special electricity rate for EV charging, often through the installation of dedicated meters. This allows households or businesses to avoid moving into higher consumption tiers, and in some cases, it can translate to up to 40% savings on electricity costs for vehicle charging [CFE, 2022].

The ISAN also favors electromobility by exempting electric and plug-in hybrid vehicles from the one-time new vehicle acquisition tax. Additionally, electric vehicles imported from countries with which Mexico has free trade agreements are exempt from the standard 16% import tariff, making EVs more accessible to the general population [Rangel, 2025].

At the state and municipal levels, several governments have implemented complementary incentives. In places like Mexico City, Jalisco, Baja California, Querétaro, and the State of Mexico, owners of electric vehicles benefit from exemptions from emissions testing, annual circulation tax waivers, free or preferential parking, and reduced toll fees.

In Mexico City, for example, plug-in hybrids receive 50% discounts on permits and vehicle registrations [Montemayor, 2019].

Beyond consumer benefits, Mexico has also created incentives to attract investment in EV manufacturing and infrastructure. Under the "Plan México" [2025–2030], companies that invest in the assembly of electric or hybrid vehicles are eligible for accelerated tax deductions of up to 86% during the initial years and 83% for subsequent years [Olguín, et al., 2025]. This policy is designed to boost national production and align with international trade agreements such as the USMCA. As part of this industrial strategy, various states offer infrastructure subsidies, tax relief, and land grants to attract automakers and battery manufacturers.

These measures have had a noticeable impact. EV sales in Mexico are growing at an estimated 25–30% annually, and projections suggest that by 2030, up to 50% of new vehicle sales could be electric. Moreover, the government is supporting the launch of a low-cost Mexican electric vehicle, named Olinia, expected to be priced between MX$90,000 and MX$150,000 [Goytia, 2025]. This project, designed to coincide with the 2026 FIFA World Cup, seeks to democratize access to electric mobility for lower-income populations.

To provide a clear overview of the fiscal and economic mechanisms currently supporting electric mobility in Mexico, Table 2 summarizes the main types of incentives available at the federal and local levels.

These incentives cover key areas such as income tax deductions, value-added tax exemptions, reduced electricity rates, and industrial support for manufacturing.

This structured summary highlights the comprehensive nature of the country's electromobility policy framework and its alignment with national and international sustainability goals:

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Box 2

Table 2

EV Incentives in Mexico

Incentive Type	Description
Income Tax Law [ISR]	Up to MX$250,000 purchase, MX$285/day lease, 30% infra support
Value-Added Tax Law [VAT/IVA]	No VAT on EV import or domestic sales
New Automobile Tax Law [ISAN]	No new car acquisition tax for EVs and PHEVs
Special Electricity Rates	Up to 40% lower with dedicated EV meters
Local/State Incentives	Tax waivers, free parking, emission exemptions, toll discounts
Industrial Incentives	83–86% depreciation for EV assembly investments

Progress in Public Policies for Electric Vehicles in Mexico

Mexico has made significant advances in designing and implementing public policies aimed at transitioning toward zero-emission electric mobility. A key pillar of this process is the ENME [Sánchez, 2023], which is part of a broader energy transition agenda that includes plans such as PRODESEN 2023–2037 and the initiative "Lithium for Mexico," focused on securing access to strategic minerals for battery production [SENER, 2021].

At the institutional level, a major milestone was the submission of ENME for public consultation through CONAMER in the second half of 2023. This process opened dialogue with key stakeholders from the public sector, private industry, and academia, consolidating a participatory vision for the development of electromobility. Subsequently, in early 2024, the Energy Regulatory Commission [CRE] issued a set of regulations to integrate electric vehicle charging infrastructure into the national electricity system. This measure provides legal certainty for investors and operators, as well as establishing technical standards for the installation and operation of chargers nationwide [Sánchez, 2023].

At the subnational level, several states have begun implementing pilot projects for transport electrification. For example, Mexico City has introduced electric buses and taxis as part of its public fleet renewal, a key step toward reducing emissions in one of the country's most polluted urban areas.

Likewise, states such as Jalisco, Puebla, Hidalgo, Monterrey, and the State of Mexico have deployed electric vehicle fleets for public transit and last-mile logistics, accompanied by the installation of public charging stations at strategic locations. These initiatives reflect growing local commitment to adopting clean technologies in mass transit and light freight [Salgado-Conrado, 2024].

The private sector has also started actively participating in this transition. A notable example is Grupo Lala, a leading food company, which incorporated 30 electric delivery trucks into its fleet as part of its strategy to reduce its carbon footprint [Grupo Lala, 2024]. Such corporate decisions represent an important step toward decarbonizing freight transport in Mexico and demonstrate that electromobility can be a viable solution in the logistics sector.

Box

Table 3

Key Milestones in Public Policies for Electric Vehicles in Mexico.

Action or Project	Year	Lead Actor	Description
ENME	2023–2024	SEMARNAT, CONAMER	National strategy publicly consulted to promote electromobility.
Regulation of charging stations by CRE	2024	Energy Regulatory Commission [CRE]	Legal integration of EV chargers into the national electricity system.
PRODESEN 2023–2037	2023	Ministry of Energy [SENER]	Energy expansion plan that includes EV infrastructure development.
"Lithium for Mexico" Project	2022	Federal Government, LitioMx	Ensures access to key minerals for battery manufacturing.
Electrification of public fleets in Mexico City	2023–2024	Mexico City Government	Introduction of electric buses and taxis.
Pilot projects in Jalisco, Puebla, Hidalgo, Monterrey, State of Mexico	2023–2024	State Governments	Electric fleets for transit and delivery; public charger installations.
Adoption of electric trucks by Grupo Lala	2024	Private Sector	Incorporation of 30 electric delivery vehicles into their fleet.

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Together, these advances demonstrate that Mexico is beginning to transform its regulatory and operational framework to effectively integrate electric vehicles into the national transportation system. While significant challenges remain —such as expanding charging infrastructure, strengthening fiscal incentives, and developing local technical capacities— the country has successfully moved from strategic planning to executing concrete projects across multiple levels of government.

Gaps in Public Policies for Electric Vehicles in Mexico

Despite significant progress in promoting electric vehicles in Mexico, important gaps remain that hinder the widespread adoption and comprehensive development of electromobility in the country. One of the main challenges is the insufficient charging infrastructure, which is mainly concentrated in urban areas and wealthier neighborhoods, leaving rural and peripheral regions underserved [Salgado-Conrado- 2025]. This uneven distribution limits access to electric vehicles for a large portion of the population and complicates the advancement of sustainable mobility nationwide. Additionally, the lack of interoperability between different charging networks creates difficulties for users and represents a barrier to establishing a cohesive national charging system.

On the other hand, economic and fiscal incentives for purchasing and using electric vehicles have limitations that reduce their effectiveness. Although benefits such as income tax deductions, exemptions from VAT, and new automobile taxes exist, these incentives often have maximum caps that exclude mid-range and high-end electric vehicles. Furthermore, the lack of clarity regarding the procedures to access these incentives and limited public awareness generate uncertainty, especially among individual consumers and small and medium-sized enterprises. The limited availability of accessible financing options further restricts the ability of many people to adopt this technology.

Fragmented institutional coordination represents another major challenge. Public policy for electric vehicles involves multiple federal, state, and municipal agencies, which can lead to duplications, regulatory gaps, and delays in updating norms.

This lack of integration makes it difficult for local policies to fully align with the national strategy, creating inconsistencies that affect the implementation and development of electromobility projects across the country.

Additionally, Mexico faces a shortage of specialized human capital training in electromobility.

The installation and maintenance of charging infrastructure, vehicle repair, and technological development require skilled professionals; however, educational offerings and technical training programs remain limited.

This deficiency could hinder sector growth and the consolidation of a competitive domestic industry that promotes sustainable electric mobility.

Another critical aspect is the lack of inclusive policies that ensure equitable access to the benefits of electromobility. So far, efforts have primarily focused on government fleets and the private sector, leaving behind low-income groups and rural communities, where access to electric vehicles and associated infrastructure is practically non-existent.

Moreover, little progress has been made in incorporating gender perspectives or addressing the specific needs of vulnerable groups within national strategies.

Finally, limited promotion of research, development, and innovation [R&D&I] in domestic electric vehicle technologies is a gap that leaves Mexico dependent on imports and restricts the growth of a strong local industry.

Without a committed push for R&D&I, it will be difficult for the country.

Table 4 shows the key gaps in public policies for electric vehicles in Mexico

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Box 4

Table 4

Key Gaps in Public Policies for Electric Vehicles in Mexico.

Policy Gap	Description	Impact
Insufficient & Uneven Charging Infrastructure	Charging stations concentrated in urban and wealthy areas; poor coverage in rural/peripheral zones.	Limits access and discourages EV adoption nationwide.
Limited & Complex Economic Incentives	Caps on tax deductions and unclear access processes; low financing availability.	Restricts affordability and adoption by individuals and SMEs.
Fragmented Institutional Coordination	Multiple agencies with overlapping roles and regulatory delays.	Causes policy inconsistencies and implementation gaps.
Lack of Specialized Training	Limited educational and technical programs on EV technology and maintenance.	Slows sector growth and limits skilled workforce.
Absence of Inclusive Policies	Focus on government and private fleets; low-income and rural communities underserved.	Exacerbates social inequality in EV access.
Limited R&D&I Promotion	Insufficient support for local innovation and technology development.	Maintains dependency on imports; hinders industry growth.

To achieve technological autonomy and international competitiveness in the electromobility sector. To bridge these gaps, Mexico must expand and diversify its charging infrastructure by encouraging public and private investment nationwide. Simplifying, broadening, and better communicating fiscal incentives, along with offering accessible financing options, are essential. Improving coordination among all government levels and strengthening technical training programs will support sector consolidation. Lastly, it is critical to design inclusive policies that benefit all social sectors and promote domestic technological development through innovation support.

Comparative Framework: Mexico vs. Latin American Cases

The transition toward electric mobility has become a strategic objective for many Latin American countries. While Mexico has laid important groundwork through its ENME, countries such as Colombia, Chile, and Costa Rica have taken more aggressive and coordinated approaches, leading to faster results in adoption and infrastructure deployment [Lehmann et al., 2025; Manrique Pérez et al., 2025]. This section compares Mexico's efforts with these successful regional examples, focusing on key dimensions such as effectiveness in EV adoption, charging infrastructure, renewable energy integration, and institutional coordination.

In Mexico, the ENME outlines long-term targets for 2030, 2040, and 2050, and is supported by fiscal incentives that include income tax deductions, VAT and ISAN exemptions, special electricity rates for EV charging, and depreciation benefits for manufacturers. However, these measures are capped, inconsistently applied across regions, and not widely known by the general population. Although regulatory steps such as those issued by CRE have begun to integrate EV infrastructure into the national grid, the pace of real-world implementation remains slow, and charging stations are still concentrated in major urban areas [Méndez & Linares, 2025].

Colombia offers a strong contrast through a well-defined legal framework [Law 1964 of 2019] that provides broad tax exemptions, reduced registration fees, toll discounts, and license plate benefits for EV owners. These incentives have contributed to one of the fastest-growing EV markets in the region. Moreover, public procurement programs have enabled the integration of electric buses and taxis in cities like Bogotá, making EVs more visible and accessible to the population [Manrique Pérez et al., 2025]. Chile has focused on electrifying public transport and developing a robust charging infrastructure through public-private partnerships [Tabares et al., 2020]. Its National Electromobility Strategy aims for 100% electrification of public buses by 2040, and the capital city Santiago now operates one of the largest electric bus fleets outside of China [Thema & Roa-García, 2023; Lehmann et al., 2025].

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Chile also benefits from a clear regulatory framework and technical standards that ensure interoperability across different charging networks, facilitating user access. Costa Rica, meanwhile, stands out for its deep integration of electric mobility with renewable energy. Nearly 99% of the country's electricity comes from clean sources, allowing EVs to be powered sustainably from day one [Viscidi, 2021]. Costa Rica's National Decarbonization Plan includes strong commitments to transport electrification, supported by import duty exemptions, state-backed financing options, and rural charging infrastructure [Rodríguez et al., 2021].

In comparison, Mexico's approach is more fragmented. Multiple federal and local agencies are involved in electromobility efforts, often without clear coordination. While the private sector is beginning to engage—with companies like Grupo Lala adopting electric delivery fleets and local automakers like Zacua and the Olinia project moving forward—there is still a lack of integration between policy, infrastructure, and industrial development. In this regard, recent analyses such as Jiménez, Peralta, and Valencia [2025] emphasize the need for comprehensive strategic frameworks like the Plan Sonora, which seeks to position Mexico as a competitive hub in the context of nearshoring and global protectionist trends. However, despite these initiatives, the articulation between regional competitiveness strategies and national electromobility policies remains limited, underscoring the necessity for a more cohesive and cross-sectoral approach. Moreover, while countries like Chile and Costa Rica are actively aligning their EV policies with renewable energy agendas, Mexico continues to rely heavily on fossil fuels in its energy mix. Without a parallel commitment to clean energy, the environmental benefits of EV adoption in Mexico could be significantly undermined [Méndez & Linares, 2025].

To better understand Mexico's position within the Latin American context, it is useful to compare its current EV policy framework with that of other leading countries in the region. Colombia, Chile, and Costa Rica have implemented targeted strategies that reflect varying levels of institutional coordination, fiscal incentives, infrastructure development, and renewable energy integration [Gómez-Ramírez & Solis-Ortega, 2021; Lehmann et al., 2025; Manrique Pérez et al., 2025].

Table 5 presents a comparative overview of these countries across key policy dimensions, highlighting both shared challenges and areas where Mexico may draw lessons to accelerate its own electromobility transition.

Box 5

Table 5

WOT Analysis – Mexico's EV Policy Environment.

Strengths	Weaknesses
- National strategy with 2030–2050 targets [ENME] - CRE regulation for integrating chargers into the grid - Support for domestic EV manufacturing [e.g., Olinia, Zacua] - Growing private sector engagement [e.g., Grupo Lala EV fleet]	- Charging infrastructure concentrated in major cities - Tax incentives capped, underutilized, or poorly communicated - Fragmented institutional responsibilities across federal and state levels - Low EV affordability and financing for middle-income and rural users
Opportunities	**Threats**
- Leverage USMCA to scale EV production and exports - Align EV rollout with renewable energy expansion - Use public investment to promote chargers in underserved areas - Promote EV technician training and R&D innovation hubs	- Slow rollout could stall competitiveness vs. regional leaders - Continued reliance on fossil fuels undermines climate benefits - Dependence on imported EV tech and batteries - Risk of widening mobility access gaps among low-income groups

To assess the strengths and limitations of Mexico's current approach to electric mobility, a SWOT analysis provides a concise overview of the internal and external factors shaping the country's policy environment. This tool helps identify what Mexico is doing well, where critical gaps remain, and what opportunities and risks lie ahead as it seeks to accelerate EV adoption. The following table outlines key strengths, weaknesses, opportunities, and threats related to Mexico's EV strategy, serving as a basis for refining public policy and guiding future action.

Recommendations for Electromobility in Mexico

Drawing from these prioritization criteria and regional best practices, a set of evidence-based policy recommendations has been formulated to guide Mexico's transition to a cleaner, more equitable transportation model.

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These recommendations emphasize interventions that are not only technically and economically viable but also aligned with global climate and development commitments.

1. *Scale up fiscal incentives.* Simplify access to tax benefits, raise deduction caps for EV purchases and infrastructure investments, and broaden VAT exemptions to increase affordability across income groups.
2. *Electrify high-impact fleets.* Prioritize the electrification of public transportation and last-mile delivery fleets, which offer strong returns on investment in terms of emissions reduction, fuel savings, and air quality improvements.
3. *Expand infrastructure beyond urban centers.* Use public-private partnerships and smart grid integration to develop interoperable, nationwide charging networks that reach underserved regions and enhance system reliability.
4. *Integrate EV policy with renewable energy.* Align vehicle electrification with Mexico’s solar and wind expansion goals to maximize environmental benefits and ensure long-term sustainability of the EV ecosystem.
5. *Build domestic capacity.* Invest in human capital development through technical training, research funding, and innovation programs aimed at reducing reliance on foreign technologies and promoting national manufacturing.

These recommendations reflect not only best practices but also Mexico’s unique policy, economic, and energy landscape. By leveraging its comparative advantages and addressing critical implementation gaps, Mexico has the opportunity to position itself as a regional leader in sustainable mobility, reinforcing its global climate leadership and delivering tangible co-benefits in health, equity, and innovation.

Conclusion

This research provides a comprehensive analysis of the public policy landscape for electromobility in Mexico, revealing both significant advancements and critical shortcomings. Despite the establishment of a strategic framework through the National Electric Mobility Strategy, the fragmented implementation and persistent regulatory gaps hinder the effective adoption of electric vehicles.

By leveraging comparative insights from successful international models and addressing identified policy deficiencies, Mexico has the potential to enhance its electromobility initiatives, ultimately contributing to sustainable development goals and reinforcing its commitment to global climate action. Future efforts should focus on fostering interinstitutional collaboration, expanding infrastructure, and increasing public awareness to ensure a robust transition towards a greener transportation ecosystem.

Author contribution

Salgado-Conrado, Lizbeth: Contributed to the generation of the idea, the development of manuscript and the establishment of the objective.

Pérez-García, Laura Andrea: Contributed to the development of methodology.

Álvarez-Macías, Carlos: Contributed to the development of the theoretical framework and the description of the existing problem and conclusion.

Availability of data and materials

The data used in this study were obtained from both primary and secondary sources. Primary data include the analysis of Mexico's regulatory frameworks related to electromobility, while secondary data were sourced from publicly accessible databases such as the Mexican Association of the Automotive Industry [AMIA], the National Institute of Statistics and Geography [INEGI], and the Mexican Electric Mobility Association. While some regional data were limited or unevenly distributed, the overall dataset is available upon reasonable request and can be accessed through official platforms or institutional reports cited in the research.

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Abbreviations

AMIA	Asociación Mexicana de la Industria Automotriz
CFE	Federal Electricity Commission
CONAMER	National Commission for Regulatory Improvement
CONUEE	National Commission for Energy Efficiency
CRE	Energy Regulatory Commission
ENME	National Electric Mobility Strategy
EV	Electric vehicles
GHG	Greenhouse Gas Emissions
ISAN	New Automobile Tax Law
ISR	Income Tax Law
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine Vehicles
INECC	National Institute of Ecology and Climate Change
INEGI	National Institute of Statistics and Geography
MW	Mega- watt
PHEV	Plug-In Hybrid Electric Vehicles
PRODESEN	National Electric System Development Program
SEMARNAT	Ministry of Environment and Natural Resources
SENER	Ministry of Energy
SRE	Ministry of Foreign Affairs
TCO	Total Cost of Ownership
USMCA	United States-Mexico-Canada Agreement
VAT	Value-Added Tax Law
ZEV	Zero Emission Vehicle

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Article

Treated Wastewater: A sustainable alternative with a microplastics perspective

Agua Residual Tratada: Una alternativa sostenible con perspectiva en los microplásticos

Tirado-Aguilar, Flor Idalia * [a], González-Moreno, Humberto Raymundo [b] and López-Méndez, María Cristina [c]

[a] National Technological Institute of Mexico / ITS of Misantla • LBH-3979-2025 • 0009-0004-0709-7222 • 787954
[b] National Technological Institute of Mexico / ITS of Misantla • LBH-9977-2024 • 0000-0002-5262-9818 • 429551
[c] National Technological Institute of Mexico / ITS of Misantla 0000-0001-8998-3397 • 377848

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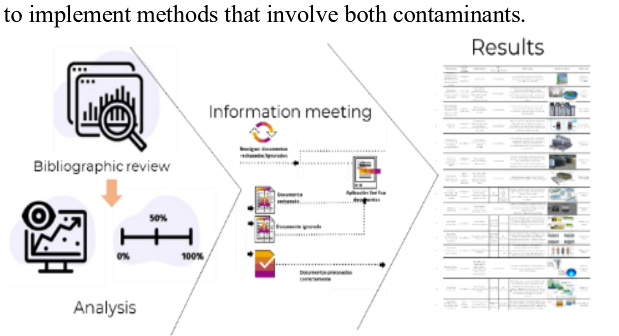
* ✉ [floridaliatirado1608@gmail.com]

Abstract

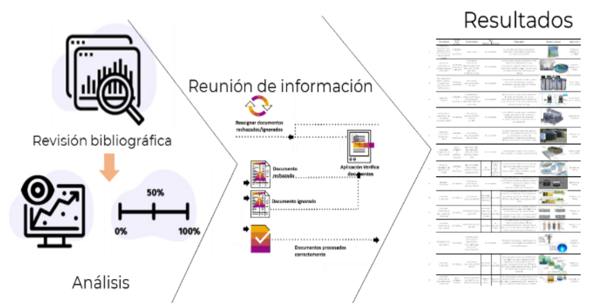
The methods used for wastewater treatment have become an indispensable process for the development of life; however, most do not consider Microplastics This analysis of 23 articles published in indexed databases identifies the discrepancy in wastewater treatment methods [WT In 2002, a study by Anaerobic Reactors reported removal efficiency of COD and BOD in industrial waters, without considering MPs; in 2020, a study reported Constructed Wetlands [CW] as efficient eco-technologies (45% - 96%) in the removal of MP used for the treatment of domestic wastewater. There is great variability in the methods and efficiencies of contaminant removal [WT& MP] and it can be attributed to the lack of specific information for their control and monitoring. This analysis underlines the need to implement methods that involve both contaminants.



Microplastics, Treated wastewater, Treatment methods

Resumen

Los métodos empleados para el tratamiento de aguas residuales se han convertido en un proceso indispensable para el desarrollo de la vida, sin embargo, la mayoría no consideran a los Microplásticos [MP] Este análisis de 23 artículos publicados en bases de datos indexadas identifica la discrepancia de métodos de tratamiento de aguas residuales [AR] En 2002 un estudio de Reactores anaeróbicos reporta eficiencias de remoción de DQO y DBO en aguas industriales, sin considerar los Mp´s, en 2020 un estudio reporta a los Humedales Construidos [HC] como ecotecnologías eficientes (45% - 96%) para el tratamiento de aguas residuales domésticas y en la remoción de MP. Hay una gran variabilidad en los métodos y eficiencias de remoción de contaminantes y MP, y se puede atribuir a la falta de información específica para su control y monitoreo. Este análisis subraya la necesidad de implementar métodos que involucren a ambos contaminantes.



Treated wastewater, Microplastics, Treatment methods

Area: Dissemination of and universal access to science

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Introduction

The contamination of water bodies by the direct discharge of wastewater WW domestic, hospital, industrial, storm water, and livestock wastewater is an activity that seriously harms the development of organisms and the health of the planet [0 & 0] Added to this is the scarcity of water available for human consumption, the demand for drinking water, the generation and presence of microplastics MP continue to increase and add to the current environmental challenges [0]

One of the sectors that benefits from the use of wastewater because it increases the input of nutrients and organic matter into the soil, increasing and maintaining its fertility, is the agricultural sector [1] However, the use of this type of water also causes harmful effects that deteriorate the quality of crops and soil. In developing countries such as Mexico, water quality parameters for discharge are often not met, mainly in rural, marginalized, and low-income areas [0] Therefore, treated wastewater has become an indispensable process for the development of life, becoming a viable alternative for obtaining reusable water [0]

There are efficient technologies for wastewater treatment such as microfilters, green filters, advanced oxidation, membrane treatment, electrocoagulation, distillation, WWTP, etc. [0], but their management and use in different activities requires high investments in infrastructure, installation, and maintenance, which makes them expensive [0].

In addition, they also generate MP, since they were not designed to retain and/or eliminate such particles [0]. To date, there is no control or regulation of MP, and the few techniques currently available for their detection and/or retention strategies are ineffective and inefficient, as their location is unknown [5] and they are considered ubiquitous [2].

The sources generating these microplastic particles have been classified as primary and secondary [5] and the food chain could be adversely affected, as MP are present in all environments [0], including untreated and treated wastewater [0].

In addition, they are continuously generated through daily activities, for example, in the agricultural sector itself [0] through the use of plastics for crop cover, plastic irrigation systems, plastic mulch, fertigation through plastic pumps, plastics (mulching) for weed control and temperature control, growing tunnels made of polyethylene sheets, shade nets and meshes, etc. [0]

A reliable alternative for the removal of contaminants in wastewater are nature-based systems, eco-technologies that achieve high percentages of efficiency in the removal of common contaminants in domestic wastewater [0] and also promise to be effective systems in the retention of microparticles [0] Constructed wetlands CW require low economic investment in construction, installation, and maintenance compared to other wastewater treatment methods [0]. Although they have mostly been used as secondary or tertiary treatments, they have become popular and have even been classified as circular economy eco-technological systems [0].

Therefore, the objective of this study is to analyze wastewater treatment methods and include reports on MP present in influent and effluent. This will allow us to identify the importance of their presence, sources of MP generation, and consider viable alternatives to address the challenges in the wastewater treatment process, retention, and/or elimination of MP.

Methodology

A documentary review of scientific articles was conducted using the search engines ScienceDirect, Google Scholar, Science Research, and Scielo. The search criteria covered a period 2002-2024 and included works in English and Spanish, using the keywords: Wastewater, Treated Wastewater, Treatment Methods, Agriculture, Microplastics, Constructed Wetlands. This review consisted of 30 articles, but only those published in indexed journals with an impact factor were filtered, and these were reduced to 23 relevant research studies. The information gathered was organized in tabular form, including the year, type of wastewater, type of treatment, and the report of the presence of MPs. Descriptive graphs of the studies found were also created for further analysis.

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Results

Progress in wastewater treatment is directly linked to the regulation of water quality parameters for discharge, which reduces pollutant discharges and protects water resources. No legislative guidelines were found in the 23 articles, although an additional search was conducted and the information was compiled in a table showing the instruments applicable to wastewater in Mexico see Table 1. It is important to distinguish the advances in the transition of the country's public policies towards the sustainability model, which are supported by legal bases, institutional frameworks, and government bodies [0]

Box 1

Table 1

Environmental regulation for AR

Instrument	Objective
Mexican Constitution	Establishes the right to a healthy environment healthy environment for their development and well-being
General Law for the Prevention and Comprehensive Management of Waste (LGPGIR)	Waste regulation
Ecological Balance and Environmental Protection (LGEEPA)	Sustainable development and lay the foundations for environmental protection
NOM-002-ECOL-1996	AR discharges to urban or municipal sewerage systems
NOM-052-SEMARNAT-2005	Hazardous waste
NOM-161-SEMARNAT-2011	Special handling waste
NOM-001-SEMARNAT-2021	Wastewater discharges

The instruments created ultimately defined the general legal framework for waste regulation in our nation at the federal level, which is based on the Political Constitution of the United Mexican States, the General Law of Ecological Balance and Environmental Protection, the General Law for the Prevention and Management of Waste, the corresponding regulations, and the Official Mexican Standards NOM that apply across all levels of government. However, the presence of emerging contaminants of concern, such as microplastics MP, is an issue that has received little consideration.

This phenomenon adds to existing environmental problems, affecting all environments [20] Due to the wide variety of polymers, a classification has been developed. MP are synthetic solid particles or polymeric matrices, with regular or irregular shapes and sizes ranging from 1 µm to 5 mm, either of primary or secondary origin. They are insoluble in water and their impacts are still unknown [0] In addition to this, methods for wastewater treatment have emerged due to the problem of water body pollution, and Figure 1 shows the distribution of studies over the period under review and the type of water considered for treatment. This analysis shows that these methods have advanced in line with the needs and requirements established by associations working to safeguard the environment and internal regulations by countries, such as those mentioned above Table 1 for Mexico.

Box 2

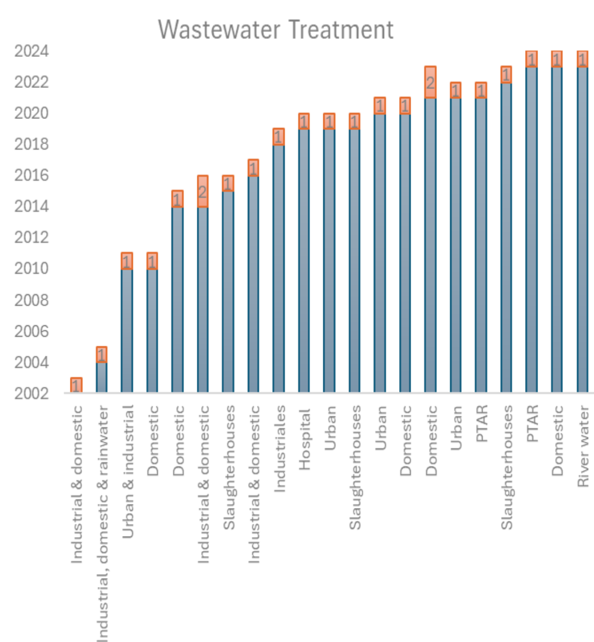

Figure 1

Studies on AR treatment.

The countries that have considered creating and integrating alternatives for wastewater treatment are shown in Figure 2. Although there have been few studies on large-scale nature-based technologies, they have gained relevance in terms of research and monitoring [0] Furthermore, studies are being promoted due to the continuous increase in the cost of using WWTPs and the impossibility of implementing them in rural areas [0]

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For example, in Mexico, there are sites where particular commitments make water reuse difficult and where rates are low, which puts the treatment and reuse of this resource at a disadvantage; without considering that the costs of treated wastewater should be compared with the actual costs of drinking water production; and that, in addition to the costs of treated water regardless of the treatment method, the cost-benefits obtained from savings in the reduction of public health problems and environmental protection should also be added, as well as considerations such as the reduction of groundwater and surface water exploitation.

However, these have not been quantitatively related, even though their impact should be considered as a side effect of treated wastewater reuse [0]

Box 3

Figure 2

Percentage of research by country.

Of the research found, 32% of wastewater treatment methods belong to Mexico, while 18% of them are centered in China, followed by Spain with 14%, Colombia, Ecuador, and Brazil with 9%, and Thailand with 5%. Finally, Japan also has a presence with 4%, corresponding to treatments with nature-based technologies.

It is worth mentioning that the processes are grouped under the names of primary, secondary, and tertiary treatment. Primary treatment includes physical operations, secondary treatment includes biological processes for the assimilation of organic matter, and tertiary or advanced treatment includes operations and processes used to remove contaminants not removed by primary or secondary treatment.

In addition to these contexts, it is understood why constructed wetlands [CW] are regularly used as secondary or tertiary treatments, also involving the type of wastewater to be treated and, therefore, the pollutant load [0]

In Mexico, an investment of $2.9 billion has been estimated to provide clean water and sanitation services to urban residents.

Therefore, billions of dollars are needed to serve the Latin American region, which makes it logical that this country accounts for 40% of the use of treated wastewater methods. In the past, alternatives for man-made wastewater treatment operations involved a number of natural treatments.

For example, on-site disposal systems septic tanks or cesspools offered a viable option for disposing of waste, but when not properly managed, they led to severe soil contamination and, consequently, disease in humans and animals [0 & 47]

Studies reveal that early wastewater treatments focused on industrial, domestic, urban, and stormwater, with 60% of studies not taking into account the presence of MP. Table 3 shows the number of studies selected and describes the type of treatment used, the type of wastewater, the contaminants reported in their disposal process, and whether these methods take into account the presence of MP in the effluent and influent, along with an observation column describing relevant information from the research, a visual reference to the type of treatment, and finally the author and year in which it was reported.

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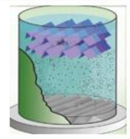
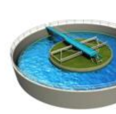
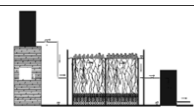
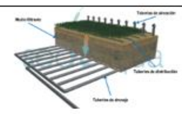
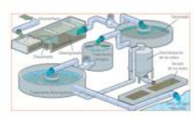
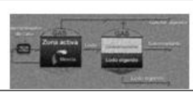
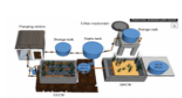
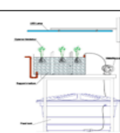
Box 4

Table 2

Methods used in wastewater treatment

No	Treatment	Type of Wastewater	Contaminant	Mp´s Effluent Inflow	Observation	Visual Reference	Author and year
1	Upflow anaerobic sludge blanket (UASB) reactors	Industrial and domestic	COD and BOD	Not reported	The rate of methane formation can be influenced by different COD concentrations.		Rodríguez-Martínez et al., (2002)
2	Primary sedimentation tank and anaerobic lagoon	Industrial, domestic, and storm water	removal efficiency BOD5: 25-40%, COD: 89%, and TSS: 50-70%. NTK: 80%, Coliforms: 5 logs	Not reported	Treatment efficiency depends on weather conditions		Gutiérrez-Sarabia et al. (2004)
3	Anaerobic filter (AF) coupled to an aerobic sequential batch reactor (SBR)	Urban and industrial	COD removal efficiency 50-81%	Not reported	The system consists of at least four cyclical processes: filling, reaction, settling, and emptying, both for effluent and sludge		López-López et al., (2010)
4	Artificial Wetlands	Domestic	BOD_5removal efficiencies 70 and 86%	Not reported	Duckweed was used, which contributed elements characteristic of the plant to the water, which increase the pH		Rodríguez et al., (2010)
5	Chemical adsorption	Industrial and domestic	Organic contaminants, COD removal efficiency 73% TOC 63% Color 84%	Not reported	This process does not completely remove impurities from water, but rather concentrates them on the surface of a solid, requiring a subsequent process to remove that solid from the water.		Torres-Pérez et al. (2014)
6	Anaerobic membrane bioreactors	Domestic	COD removal efficiency: between 85 and 93%.	Not reported	Requires large amounts of energy to maintain aerobic conditions		Ruigómez et al. (2015)
7	Sequencing batch reactors (SBR)	Industrial and domestic	COD removal efficiency 54% NT 60%	Not reported	Includes anaerobic, aerobic, anoxic treatment, including sedimentation. All these operations are carried out in the same reactor		Muñoz et al. (2014)
8	Vertical flow constructed wetlands	Wastewater from pig slaughterhouse	COD: 36%; BOD: 66%; Coliform bacteria: 97%; Fecal bacteria: 99%	Not reported	Large-scale wetland with a TRH of 5 days, adapted with Typha ornamental plants		Pitaktunsakul et al., (2015)
9	Wastewater Treatment Plants (WWTP)	Industrial and domestic	BOD, COD (70%), TSS, Phosphates, Total Coliforms, Fats and Oils	NR / reported (Fibers 28.7%, Pellets 10%, Fragments 61.3%)	The largest source of MP in water bodies includes wastewater from WWTPs, landfills, and industrial areas.		Sarria et al. (2016)
10	Advanced oxidation using modified Fenton	Industrial	COD 44.4%, BOD_5 12.54%	Not reported	The Fenton reaction was carried out at 20 °C and improves the biodegradability ratio until treatment can be achieved in a conventional system.		Sánchez et al., (2018)
11	Anaerobic digestion	Domestic	Ammonia removal efficiency: 80.4%	Not reported	Fermentation process, characterized by the conversion of organic matter into methane and CO2.		Akizuki et al. (2019)
12	Hybrid system of artificial wetlands	Urban	COD 69% TSS 99% NH_4 91% $P\text{-}PO_4^{3}$ 96%	Not reported	VFCW-HFCW hybrid system. The effluent was always suitable for discharge into the environment.		Rousso et al., (2019)
13	Underground constructed wetlands	Hospital	95.6% ethinylestradiol 91.2% bisphenol A 100% levonorgestrel	Not reported	Laboratory-scale wetland, three with gravel, one with *Cyperus isocladus*, another with *Eichhornia crassipes*, and one without macrophytes		Campos et al. (2019)

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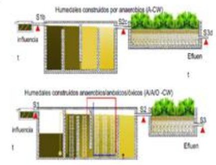
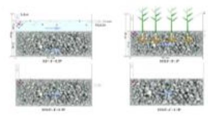
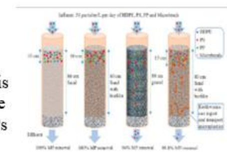
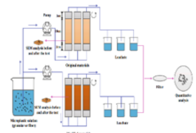
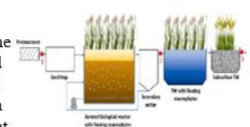
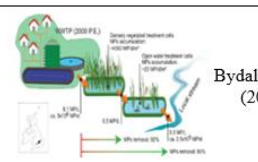
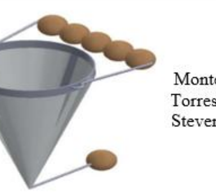
RENIECYT: 1702902

No	Treatment	Type of Wastewater	Contaminant	Mp´s Effluent	Inflow	Observation	Visual Reference	Author and year
14	Constructed Wetlands	Domestic	45% removal of suspended solids	Reported (430-2154 MP/m³)	NR	Anaerobic/anoxic/oxidation processes. The polymer influential is polypropylene (PP, 54.6%), followed by polystyrene (PS, 29.7%) and polyethylene terephthalate (PET, 9.7%).		Su Wei et al. (2020)
15	Electrocoagulation	Urban	99% removal of MPs	5 g/L	NR	Optimal reactor conditions: pH=7.5, NaCl concentration=0-2 g/L, and current density=11 A/m².		Peláez Villa Simón (2020)
16	Constructed wetlands with horizontal surface flow	Domestic	MP removal of 81.63%	Reported (films, fragments, and fibers)	NR	The combination of biofilms and physical filtration played an important role in MP retention.		Yuling et al. (2021)
17	Vertical flow Constructed Wetlands	Domestic	96% removal of MP	Reported		Filter media: sand, gravel, and worms; Worms influence the transport of MPs; there is no significant difference in the % removal of MPs without worms.		Wang, et al. (2021)
18	Urban Wetlands Treatment	Urban	PT, NT, DQO, CE, G/A, OCT, OCF	Not reported		The original design flow rate of this treatment system was 3.33 l/s, for a population of 2,953 inhabitants (2005), with temperatures ranging from 15.9 to 22.9 °C, annual precipitation of 1,048 mm, and a useful life of 20 years.		Castañeda, (2021)
19	Aluminosilicate filter media	WWTP	96% removal of MP and MP fixation capacity of PE and PA.	NR	granular polyethylene (PE, 10 µm) and fibrous polyamide (PA, 100 µm)	Morphological retention mechanisms: captured, trapped, and entangled		Maocai et al., (2021)
20	Photolysis (PHO) and Photo-Fenton	Slaughterhouses	PHO-HSPF achieved efficiencies of 84.5–91.6% and 95.8–99.9% for COD and color, respectively	Not reported		Microbiological practice contaminated with dyes and pathogenic microorganisms. With direct photolysis.		Garduño-Pineda et al., (2022)
21	Constructed Wetlands with Horizontal Underground flow	Wastewater from WWTP	Overall efficiencies of 97.42% in the removal of MP	Reported (20.3 MP/L)	Reported 0.58 MP/L)	Roots play an important role in retaining MPs, as the complexes formed adhere to MPs; in addition to being a secondary treatment system		Calzadilla et al. (2023)
22	Constructed Wetlands	Domestic	95% MP removal efficiency	Reported (6 MP/L)	NR	Secondary treatment, most MP's were trapped within 20% of the HC conditioned for sedimentation and shallow vegetation treatment cells.		Bydalek et al. (2023)
23	Device for the removal of microplastics in rivers	River water	Removal rate is 83.16%	NR	16.84% of remaining MP have not been filtered	Maximum MP retention capacity of 6.54 l and weight of 1.15 kg, a value of $115 for commercialization.		Montesdeoca Torres Brayan Steven (2023)

NR: Not reported

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The treatments have reported overall removal efficiencies of 45%. Specifically, the contaminants analyzed in their purification are BOD, with reported efficiencies of 25-40-70%; COD: 50-70-73-80-89 and 93%; and TSS: 50-70%. NTK: 81-85%, Color: 84%, NT: 60%, Coliform bacteria 97%. Fecal bacteria 99%, Phosphates, Total Coliforms, fats and oils, Ammonia removal efficiency of 80.4% and in terms of MP removal 81.63%, 95 and 96%, and one study reports up to 97.42% MP retention.

Although technology exists to produce drinking water from treated wastewater effluents, treated wastewater is mostly used as cooling water in industrial applications, irrigation such as golf courses and public lawns and non-potable domestic use such as toilets [0]

In 2015, Pitaktunsakul et al. adapted their study of large-scale vertical flow constructed wetlands for the treatment of slaughterhouse wastewater, reporting removals of 70% in COD, 66% in BOD, 97% in coliforms, and 99% in fecal bacteria. Given these high removal efficiencies, they mention that this could be due to the hydraulic retention time HRT of 5 days and that the adaptation of a type of ornamental plant *Typha* had an influence. In addition, the treated water met the minimum requirements for discharge and was directed to a nearby body of water.

However, they do not report the inflow or outflow of MP. In 2016, Sarria et al. published an article on Wastewater Treatment Plants WWTP with 70% removal efficiencies in COD, BOD, TSS, FOS, fats, and oils, which treat wastewater from industrial and domestic sources. Although the presence of MP in the effluent is not reported, they do report them in the effluent, where 28.7% were fibers, 10% pellets, and 61.3% fragments. They report that the largest source of MP generation in water bodies includes wastewater from WWTPs and runoff from urban areas, landfills, and industrial areas.

CW studies report different designs in terms of size, flow, and adaptation with ornamental plants, mostly placing them as secondary or tertiary treatments. A study of constructed wetlands in 2020 by Su Wei in China was found, in which domestic wastewater was treated using three different processes: anaerobic/anoxic/oxidation.

The effluent was reported to be 430-2154 MP/m^3 and reported a type of polymer in the influent, polypropylene PP, 54.6%, followed by polystyrene (PS, 29.7%) and polyethylene terephthalate (PET, 9.7%). However, no evidence of any common wastewater contaminants was found. Yuling et al., in 2021, published a study using CW, but with horizontal subsurface flow, reporting an efficiency of 81.63% in the removal of MP, taking into account that the union of biofilms and physical filtration played an important role in the retention of MP. The morphological characteristics of the MP and the openings in the substrate are related to their transport. In this treatment system, the treated water was directed to a sewer because it was on a laboratory scale. Another study in 2021 on vertical flow CW, also on a laboratory scale, Wang et al. used sand, gravel, and earthworms as filter media; earthworms had a considerable influence on the transport of MP, but there was no significant difference in the percentage of MP removal in wetlands without earthworms.

Conclusions

Sixty percent of the studies analyzed do not consider the presence of microplastics; however, they reveal that initial wastewater treatments focus on industrial, domestic, urban, and stormwater. Advances in the transition of the country's public policies toward a sustainability model are supported by legal bases, institutional frameworks, and government bodies [0]

The studies can even be clarified according to the socioeconomic status of the countries that have implemented wastewater treatment technologies, see Figure 5. Likewise, the instruments created defined the general legal framework for waste regulation in our nation, based on the Political Constitution of the United Mexican States, the General Law of Ecological Balance and Environmental Protection, the General Law for the Prevention and Management of Waste, the corresponding regulations, and Mexican Standards that have been adapted in accordance with legislative considerations that promote and seek to reduce pollutant discharges and protect water resources [0]

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Box 5

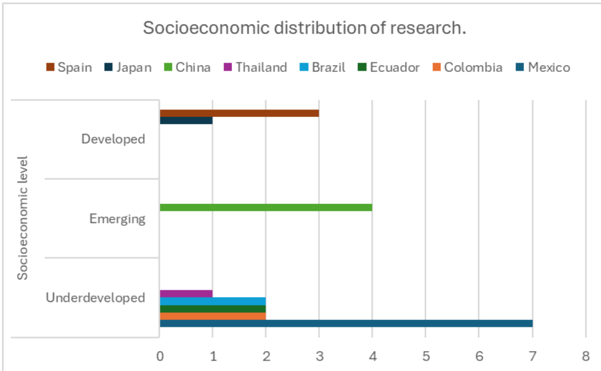

Figure 3
Socioeconomic classification of research

The classification of studies according to the socioeconomic level of countries reveals that there may be a relationship with research and implementation of low-cost wastewater treatment technologies. Underdeveloped countries have the highest number of wastewater treatment studies, while an emerging country such as China has only four relevant studies on this type of water treatment in the period under review. Despite the small number of studies found, those from developed countries such as Spain and Japan have been cited in studies from developing countries. However, no relationship was found between this, nor was there any correlation between the search for, research into, and implementation of technologies for wastewater treatment and government laws for the mitigation of water pollution, much less the involvement of Emerging Pollutants of Concern such as Microplastics.

Only 40% of the studies analyzed considered the presence of microplastics in the effluent, influent, and/or both. However, no evidence was found of efficiency in the removal of common pollutants in wastewater at the same time as the removal and/or elimination of MP in the studies. Despite this, constructed wetlands are considered efficient methods for retaining MP, with their different configurations of size, substrates, and planting [0]

Of the research found, 32% of wastewater treatment methods belong to Mexico, while 18% of them are centered in China, followed by Spain with 14%, Colombia, Ecuador, and Brazil with 9%, and Thailand with 5%. Finally, Japan also has a presence with 4%, corresponding to treatments with nature-based technologies.

It would be important to consider the impact of socioeconomic status on the implementation of wastewater treatment methods and correlate these variables to determine industrial, agricultural, cultural, and other economic factors that contribute to pollution, population growth, and water scarcity problems.

None of the articles reported on the reuse of treated wastewater for agricultural activities. However, the problem of water scarcity for human consumption is directly linked to this sector, as it accounts for the largest percentage of water available on the planet (70%). All treated water reported was directed to nearby water bodies and/or sewers [0 & 0] Therefore, it would be advisable to conduct a more exhaustive and specific search on the use of this type of water in the agricultural sector to meet its demand with reliable alternatives such as CW, also considering the circular economy [0]

What was reported was that the agricultural sector benefits from the use of wastewater because it increases the input of nutrients and organic matter into the soil, which increases and maintains its fertility [1] However, it also causes harmful effects that deteriorate the quality of crops and soil [0] and the presence of MP has been completely overlooked [0]

The impacts of MP, the use of treated and untreated wastewater, and common practices are challenges that remain unaddressed, mainly by the agricultural sector.

These circumstances should be included in future studies. The reuse of treated water for agricultural activities, ensuring quality requirements, could be a viable alternative to address the problem of water scarcity, considering that the agricultural sector uses 70% of the water available for human consumption.

Therefore, conceptualizing the importance of including the presence of MP due to their harmful impacts on nature, and the use of nature-based eco-technologies such as constructed wetlands adapted with ornamental plants reported as efficient systems for MP retention [0] could function as secondary or tertiary treatments.

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Addressing current environmental problems jointly is a challenge for science and for all the organizations involved. Solutions must be created that lead to real changes in common practices and decisive improvements. A specific case is the treatment of wastewater (domestic, industrial, storm water, agricultural, and hospital) as a viable alternative to water scarcity. Constructed wetlands are nature-based technologies with low investment, maintenance, and energy costs compared to other technologies such as WWTPs.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no known financial interests in conflict or personal relationships that could have influenced the article presented in this article.

Author contribution

The contribution of each researcher in each of the points developed in this research was defined based on:

Tirado-Aguilar, Flor Idalia: Carried out the method and research technique, systematized the information, generating the table of studies analyzed, and wrote the article.

González-Moreno, Humberto Raymundo: Reviewed the analysis of treatment method information and systematized results.

López-Méndez, María Cristina: Performed the data analysis and systematization of results.

Availability of data and materials

The data is available on the web, created using the authors' own resources. Please refer to the bibliography and authors' emails for availability.

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Abbreviation:

1. Microplastics (Mp´s)
2. Wastewater (WW).
3. Chemical oxygen demand (COD)
4. Biochemical Oxygen Demand (BOD)
5. Constructed Wetlands (CW)
6. Wastewater Treatment Plant (WWTP)
7. Official Mexican Standards (NOM)
8. Total Suspended Solids (TSS)
9. Total Kjeldahl Nitrogen (TKN)
10. Total Nitrogen (TN)
11. Hydraulic Retention Time (HRT)
12. Vertical Flow Constructed Wetland (VFCW)
13. Horizontal Flow Wetland (HFW)

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Background & Basics

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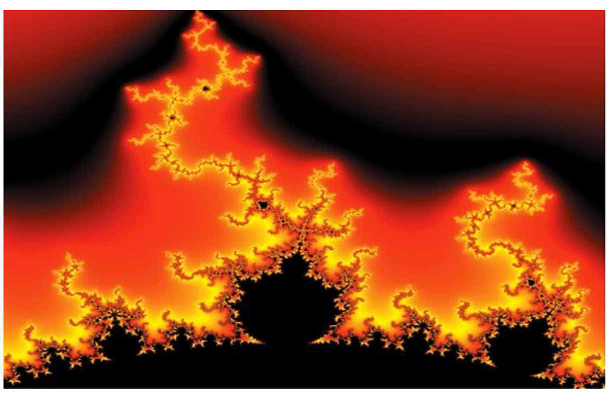

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