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Journal of Technological Engineering

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Support the international scientific community in its written production Science, Technology and Innovation in the Field of Engineering and Technology, in Subdisciplines of sources innovation in electrical, engineering signal, amplification electrical, motor design science, materials in electrical power, plants management and distribution of electrical energies.

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Knowledge Area

The works must be unpublished and refer to topics of sources innovation in electrical, engineering signal, amplification electrical, motor design science, materials in electrical power, plants management and distribution of electrical energies and other topics related to Engineering and Technology.

Presentation of Content

As first article we present, *Analysis of a homokinetic joint subjected to torsional stresses as an educational innovation based on a case study*, by Razón-González, Juan Pablo, García-Guzmán, José Miguel, Gallardo-Alvarez, Dennise Ivonne and Cano-Lara, Miroslava, with secondment at the Tecnológico Nacional de México/ITS de Irapuato as the second article we present, *Simulation of the flood zone for an extraordinary rainfall*, by González-García, Cruz, González-Trinidad, Julián, Júnez-Ferreira, Hugo Enrique and Robles-Rovelo, Cruz Octavio, with affiliation at the Universidad Autónoma de Zacatecas "Francisco García Salinas", as the third article we present, *Prototype of an energy management system for a two-seater urban solar transport vehicle*, by Arellano-Yáñez, Ricardo, Moreno-Granados, Tomas, Ortiz-Negrete, Carmela and Calvillo-Valdez, Oscar Daniel with affiliation at the Universidad Tecnológica del Norte de Aguascalientes, as next article we present, *Green wall design for rainwater harvesting for human consumption* by Veyna-Gómez, Ana Isabel, Júnez-Ferreira, Hugo Enrique, González-Trinidad, Julián and Robles-,Rovelo Cruz Octavio, with assignment at the Universidad Autónoma de Zacatecas "Francisco García Salinas", as next article we present, *PetPin: Smart GPS and NFC Collar for Pets* by Pereda-Crisanto, Alexander, Gómez-Méndez, Zaid Emmanuel, Prado-Pineda, Brayan Antonio and Lima-Arrona, Fernando, with assignment at the Universidad Tecnológica Fidel Velázquez, as next article we present, *Smart Roots*, by Anaya-A, Romina Suleima, Barriga-C, Alexander, Estrada-R, Erick Omar and Hidalgo-Baeza, María del Carmen, with assignment at the Universidad Tecnológica Fidel Velázquez, as last article we present, *Synthesis and application of aluminum-acetylacetonate-based material for the adsorption of fluoride from water*, by Ramírez-Contreras, Yeairim Elena, Ramírez-de-Alba, Daniel, Maldonado-Ríos, Juan José and Pérez-Tavares, José Antonio, with assignment at the Centro Universitario de los Lagos, Universidad de Guadalajara.

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Analysis of a homokinetic joint subjected to torsional stresses as an educational innovation based on a case study

Análisis de junta homocinética sometida a esfuerzos de torsión como innovación educativa basada en caso de estudio

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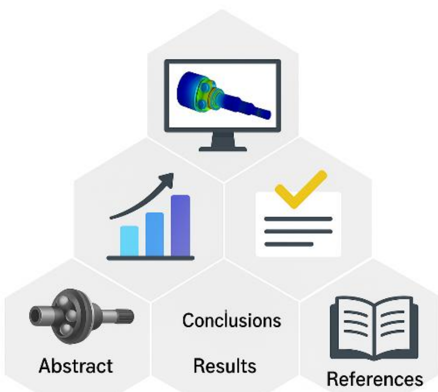
Abstract

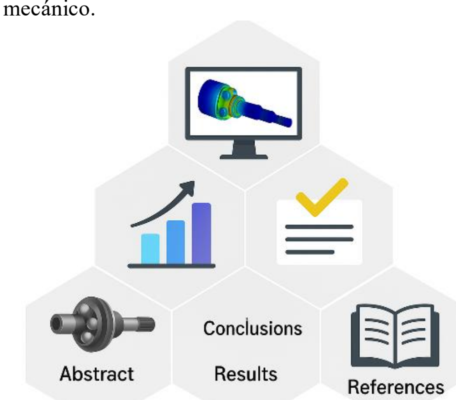
The evolution of industry 4.0 calls for a rethinking of teaching-learning models in engineer training. This paper analyzes the impact of project-based learning and the integration of design and simulation tools such as SolidWorks® and ANSYS®, supported by the finite element method and fatigue theory, in the acquisition of key industrial competencies. The results highlight the relevance of implementing innovative educational strategies based on real-world case studies in mechanical design.



Educational Innovation, Finite Element Method, CAD/CAE Analysis

Resumen

La evolución de la industria 4.0 exige un replanteamiento de modelos de enseñanza-aprendizaje en la formación de ingenieros. Este trabajo analiza el impacto del aprendizaje basado en proyectos y la integración de herramientas de diseño y simulación como SolidWorks® y ANSYS®, sustentadas con el método de elementos finitos y teorías de fatiga, en la adquisición de competencias clave para la industria. Los resultados subrayan la importancia de aplicar estrategias innovadoras en la formación basada en casos reales de diseño mecánico.



Innovación Educativa, Método de Elementos Finitos, Análisis CAD/CAE

Area: Dissemination and universal access to science

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Introduction

The boom in the automotive sector in the state of Guanajuato, particularly in the Bajío industrial corridor, reached a turning point almost three decades ago with the installation of the General Motors plant in the municipality of Silao. This event marked the beginning of a solid industrial infrastructure, catalysing the growth of industrial parks and attracting public and private investment. As a result, an ecosystem of supplier companies has been created that provide specialised inputs and services to large assembly plants, which represent one of the main sources of employment for graduates of programmes such as Electromechanical Engineering [Razón-González, 2019].

Transnational automotive companies operate under rigorous international quality standards, which require graduates to have certified technical skills that guarantee their effective insertion into the global market. Accordingly, the mission of the National Technological Institute of Mexico [TecNM] emphasises the provision of relevant, high-quality educational services that promote an equitable and sustainable society [TecNM, 2014].

The growth of the automotive cluster has accentuated the need to integrate cutting-edge technologies into design and manufacturing processes, with the aim of optimising costs, ensuring quality and offering competitive products. In this scenario, the continuous updating of teachers and their links with the productive sector becomes indispensable for strengthening institutional objectives in the academic and technological fields [Hernández, 2018].

The use of CAD/CAE/CAM tools in the classroom is an effective strategy for linking theoretical knowledge with real-world problem solving, in line with the mentefactura approach. Although the term 'mentefactura' may seem recent, it was introduced in 2012 by Juan José Goñi Zabala as part of a proposal to transform the production model through the strategic use of knowledge.

This philosophy, in conjunction with the principles of Industry 4.0, promotes the intensive use of information and its conversion into useful knowledge, leading to more efficient and innovation-oriented industrial processes [Goñi Zabala, 2012; Granados, 2020].

This context of digitalisation and automation poses new challenges for engineering education, as it requires graduates who are capable of solving complex problems, using emerging technologies and learning actively. Industry 4.0, together with mindfacturing, has led to the transformation of educational models towards more dynamic approaches, where practice-based learning and the acquisition of cross-cutting skills take centre stage.

Under this premise, this study examines an applied case of fatigue analysis in an automotive constant velocity joint, using tools such as SolidWorks® and ANSYS® to support the development of technical skills through active methodologies.

In automotive design, end-user safety and reliability are key elements, which requires detailed analysis of stresses, kinematics, and operating conditions using CAD and CAE tools. Finite element analysis allows the prediction of stress distribution and the evaluation of material behaviour under cyclic loads, including the calculation of fatigue cycles and safety factors, which are essential aspects for the reliability of mechanical systems.

Engineering education has shifted towards student-centred pedagogical approaches. Project-Based Learning [PBL] and Case-Based Learning [CBL] are widely recognised approaches for their effectiveness in strengthening critical thinking and complex problem solving [Prince, 2004; Hmelo-Silver, 2004].

The incorporation of simulators and design software allows theoretical concepts to be validated without incurring high experimental costs, thus optimising teaching resources [Budyna & Nisbett, 2020].

This paper documents a training experience in which Electromechanical Engineering students carried out the modelling, simulation and analysis of stresses in constant velocity shafts, using CAD tools and finite element simulations. Based on the identification of the problem, a solution was designed based on engineering criteria and the results were validated with specialised software, demonstrating the educational value of ABC in consolidating technical skills.

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The results show that this methodology promotes a deep understanding of fundamental concepts and strengthens students' preparation to face real challenges. Consequently, engineering education requires pedagogical environments that stimulate meaningful learning. Case-based learning represents an effective strategy for connecting theoretical knowledge with practical situations, promoting applied research, peer collaboration, and the development of skills aligned with the demands of modern industry.

State of the art

Over the last few decades, engineering education has evolved from traditional models focused on the one-way transmission of knowledge to approaches that promote active student participation in the learning process. Among these methodologies, Project-Based Learning [PBL] and Case-Based Learning [CBL] stand out, both of which have been shown to significantly improve motivation, analytical skills, and complex problem-solving in real-world contexts [Prince, 2004; Hmelo-Silver, 2004].

In particular, CBL has gained relevance in the teaching of technical disciplines by allowing students to analyse real-world situations, formulate viable solutions and develop critical thinking skills. This teaching strategy is aligned with the objectives of training engineers in the context of Industry 4.0, where there is a demand for autonomous, innovative professionals who are capable of adapting to highly technological environments.

At the same time, the integration of Computer-Aided Design [CAD] and Finite Element Analysis [CAE] tools has become an essential resource for linking theory with practice. These technologies make it possible to model mechanical components, evaluate their structural behaviour under real operating conditions, and validate designs without the need for physical prototypes, which significantly reduces development costs and times [Budyna & Nisbett, 2020].

Recent studies have documented the effectiveness of using software such as SolidWorks® and ANSYS® in developing technical skills in engineering students, especially in the analysis of stresses, deformations, and fatigue phenomena in mechanical systems.

This type of analysis contributes to a deep understanding of fundamental concepts such as safety factor, critical stress concentration zones, and resistance to cyclic loads, which are essential in industrial applications, particularly in the automotive sector.

In this context, this article is part of a line of applied research that combines the use of CAD/CAE technologies with active learning methodologies. Through the study of a real case—the analysis of a constant velocity joint—we seek to demonstrate how the implementation of CAA can enhance the development of professional skills and promote a more relevant, contextualised, and innovative engineering education.

Methodology

This study was developed as part of a training experience within the **Computer-Aided Design and Engineering** course of the Electromechanical Engineering programme at TecNM Campus Irapuato. A methodological approach based on **Case-Based Learning [CBL]** was adopted, which allows theoretical knowledge to be linked to professional practice, promoting the development of technical, analytical and collaborative skills in students.

1. Selection of the case study

The case selected was the **structural analysis of a constant velocity joint**, as shown in Figure 1, an essential component in vehicle power transmission systems. This element is subjected to cyclic torsional loads, and its study allows for an integrated approach to concepts of stress, deformation, material resistance and fatigue behaviour.

The case was chosen for its industrial relevance, mechanical complexity and direct applicability in the automotive sector of the Bajío corridor.

Box 1

Figure 1
CV joint a] with bearings b] complete

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2. Three-dimensional modelling in SolidWorks®

The first phase of the project consisted of parametric three-dimensional modelling of each of the parts that make up the constant velocity joint: outer bell, ball cage, inner balls, inner splined part, and splined shaft.

The students used SolidWorks® to create .sldprt files, defining revolution, extrusion, cut, and precise geometric adjustment operations. Subsequently, the complete assembly was carried out in an .sldasm file, establishing position and movement relationships using ‘coincident,’ ‘centred,’ and ‘aligned’ constraints, as shown in Figure 2.

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Box 2

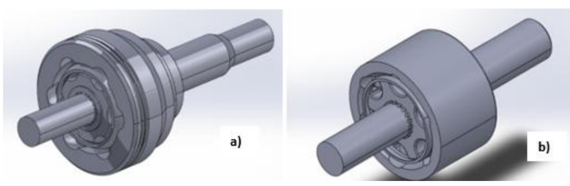

Figure 2
CV joint assembly, a] wheel side, b] housing side

3. Structural analysis setup in ANSYS® Workbench

Once the modelling was complete, the assembly was exported to **ANSYS® Workbench** for structural analysis using the **Finite Element Method [FEM]**. At this stage, the students configured the simulation environment by following these steps
:

- **Assignment of materials:** Hardened and tempered AISI 4045 steel was selected, with mechanical properties previously documented in ASTM standards: modulus of elasticity, ultimate stress, yield stress, density and Poisson's coefficient.

- **Definition of contacts:** Contacts between moving components were defined as frictionless or bonded, using the augmented Lagrangian formulation, which guarantees adequate coupling to transmit load and correctly simulate the interaction between parts.

- **Boundary conditions:** The end of the splined shaft was fixed by means of fixed supports, and a torsional torque was applied to the bell, simulating the typical torque transmission condition in operation [figure 3].

Box 3

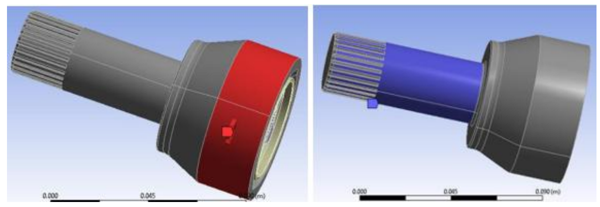

Figure 3
Boundary conditions: Fixed support [blue] and momentum [red].]

- **Meshing:** A high quality tetrahedral element mesh was implemented, using a mesh size control of 1.5 mm in critical contact areas and 2 mm in areas of low stress concentration. A mesh convergence study was carried out to ensure that the element size provided accuracy without compromising computational efficiency, the 1mm edge mesh can be seen in figure 4.

Box 4

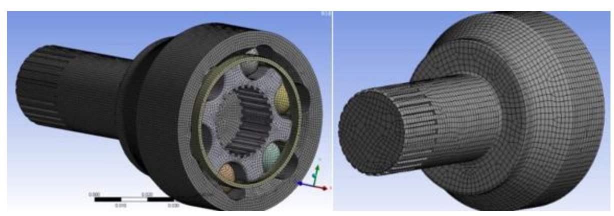

Figure 4
Mesh composed of tetrahedral elements with edge size 1mm

4. Simulation and analysis of results

During the simulation, Von Mises equivalent stress, shear stress and nodal displacements maps were generated, which allowed the identification of stress concentration zones, torsional behaviour of the material and potential fatigue failures. With these data, the factor of safety [FS] was calculated and the number of cycles to failure under a cyclic loading regime was estimated, using Goodman's criteria modified by Soderberg, as shown in figure 5.

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Box 5

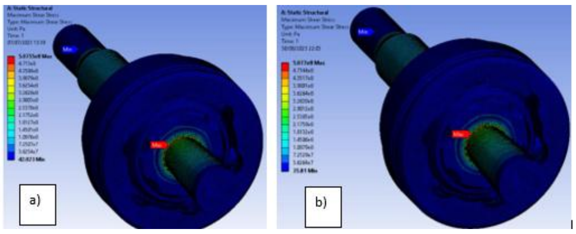

Figure 5
Von-Mises stress a] and b] shear stress within the safe allowable range

5. Documentation and pedagogical reflection
Each team of students prepared a technical report documenting:

- The design rationale.
- The modelling and simulation process.
- The interpretation of results.
- The mechanical redesign recommendations based on the analyses performed.

In addition, as part of the pedagogical reflection, a group discussion was held on the experience, the applicability of the knowledge acquired and its relevance in the automotive sector work environment.

6. Evaluation of the educational impact

Finally, a **competency-based assessment rubric** was applied to evaluate student performance in areas such as CAD/CAE software proficiency, critical data analysis, teamwork, technical communication, and application of knowledge in real-world contexts. This assessment was supplemented by self-assessment and peer co-assessment.

Results

The results obtained from the structural analysis of the constant velocity joint validated both the mechanical design of the component and the effectiveness of the teaching methodology based on real cases. The main technical and educational findings derived from the modelling and simulation process are detailed below.

1. Structural behaviour under load

The analyses performed using the Finite Element Method [FEM] in **ANSYS® Workbench** showed that the joint components operate within the **elastic range of 4045 steel**, the material used in their manufacture.

The **Von Mises** equivalent stress maps showed maximum concentrations located in the contact areas between the spheres and the retaining cage, as well as in the coupling between the splined shaft and the inner core.

The maximum stress value obtained was 478 MPa, below the elastic limit of the material [approximately 585 MPa], indicating a safe operating condition for the simulated load levels. The maximum displacements recorded did not compromise the functional integrity of the assembly, and the stress distribution patterns were consistent across different mesh configurations.

2. Mesh and convergence study

A mesh convergence analysis was performed using three different configurations [3 mm, 2 mm, and 1.5 mm]. The results showed a **significant improvement in accuracy** as the element size was reduced, with a difference of less than 2% between the solutions of the last two configurations. The mesh with **1.5 mm tetrahedral elements** was identified as the most suitable for balancing accuracy and computational efficiency.

3. Fatigue evaluation and safety factor

Based on the stresses obtained, the **safety factor [SF]** was estimated using the **modified Goodman** criterion. The calculated value was **1.82**, confirming the component's resistance to cyclic loads under normal operating conditions.

An **estimate of the number of cycles to failure** was also made, considering the typical torsional load regime of a utility vehicle, concluding that the joint could operate reliably for more than 1 million cycles [Figure 6].

Box 6

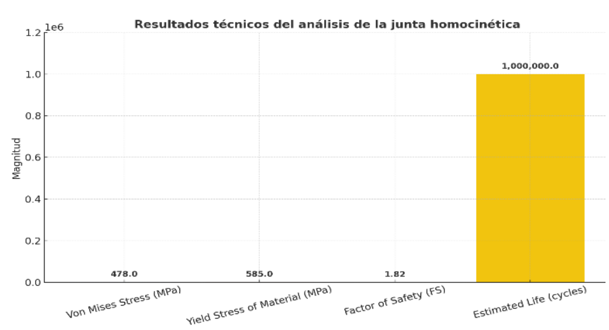

Figure 6
Results of the CV joint analysis

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4. Impact on student learning

From a pedagogical point of view, students showed significant improvement in their understanding and application of the concepts of material resistance, stress, fatigue analysis, and mechanical design.

The development of parametric models in SolidWorks®, the interpretation of results in ANSYS®, and the technical writing of the final report fostered the development of key skills such as technical communication, collaborative work, and informed decision-making.

The products generated by the work teams included:

Complete and assembled three-dimensional models.

Simulation reports with graphic evidence.

Comparative analyses between mesh configurations.

Recommendations for improvements in component design.

The teachers involved in the experience applied a competency-based rubric that showed **satisfactory and outstanding** performance levels in more than 85% of the participating students.

This experience allowed for the effective linking of theoretical content with the resolution of real problems in the professional environment.

Conclusions

The development of this study validated the use of Case-Based Learning [CBL] as an effective pedagogical strategy for linking theoretical knowledge with real situations in the industrial environment. Through the modelling and structural analysis of a vehicle constant velocity joint, students applied key concepts of materials mechanics, computer-aided design [CAD], finite element analysis [CAE] and evaluation of operating conditions under cyclic loads.

From a technical standpoint, the results demonstrated that the system components operate within the elastic range of the selected material [4045 steel], ensuring the structural reliability of the design.

The equivalent Von Mises stresses and shear stresses presented consistent and safe patterns, validated by a mesh convergence study. Likewise, the fatigue simulation yielded a favourable safety factor, confirming the component's viability for automotive applications.

In terms of training, the experience allowed students to develop analytical, collaborative, and technological skills aligned with the demands of the Fourth Industrial Revolution. The use of tools such as SolidWorks® and ANSYS® not only facilitated the visualisation of the mechanical behaviour of the systems but also strengthened technical interpretation and informed decision-making skills.

Furthermore, this study highlights the importance of human talent as a central axis in industrial innovation processes. The training of engineers capable of solving real problems using advanced technologies must be supported by a solid theoretical foundation that allows them to design, simulate, analyse and interpret complex systems with responsibility and critical vision.

Finally, it is concluded that the integration of real cases and computer simulations in the classroom contributes significantly to the improvement of the teaching-learning process in engineering, promoting a comprehensive and relevant education that links theory with practice, preparing students to successfully face the challenges of today's productive environment.

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Simulation of the flood zone for an extraordinary rainfall

Simulación de la zona inundable ante una precipitación extraordinaria

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Abstract

The presence of rainfall in a specific region can have a favorable impact by recharging aquifers and increasing storage volume in dams or reservoirs. However, when land use has changed from its natural behavior, it can cause flooding. The objective of this research was to simulate an extraordinary precipitation event in the Matamoros in a Mexican river by using an algorithm, which uses steady-flow water surface profiles modeled for gradually varied flow, the system can handle an entire channel network, a dendritic system, or a single river reach. The results indicate that for a design rainfall of 10,000 years return period the extraordinary flood will generate an elevation of 15 cm [2233.75 m.a.s.l.] over the crown [2233.6 m.a.s.l.], so under this scenario it is considered an account with hydrological risk. Also, it was obtained that for a controlled discharge for a return period of 10,000 years the affected urban area would be 143 hectares, impacting approximately a population of 5,940 in the study area.

Goals
Extraordinary rainfall
Simulation
Determine flood areas
Determine preventative actions.

Findings:
The affected urban area would be 143 hectares, impacting approximately a population of 5,940 in the study area.

Contributions:
The development of predictive models for areas prone to flooding due to extraordinary rainfall.

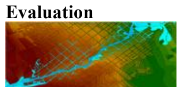
Method

Adquisition
Topography
Vegetation Type
Soil Type
Hydrological properties

Preprocessing
Rainfall-runoff, based on the data obtained.

Model
Rainfall runoff
Hydrological
Hydraulic
Integrated hydrological-hydraulic.

Evaluation



Maximum Rainfall, Flow, Flood, Simulation

Resumen

La presencia de lluvia en una región específica puede tener un impacto favorable al recargar los acuíferos y aumentar el volumen de almacenamiento en presas o embalses. Sin embargo, cuando el uso del suelo ha cambiado de su comportamiento natural, puede causar inundaciones. El objetivo de esta investigación fue simular un evento de precipitación extraordinaria en el río Matamoros en un río mexicano mediante el uso de un algoritmo, que utiliza perfiles de superficie de agua de flujo constante modelados para flujo gradualmente variado. El sistema puede manejar una red completa de canales, un sistema dendrítico o un solo tramo del río. Los resultados indican que, para una precipitación de diseño de 10,000 años de período de retorno, la inundación extraordinaria generará una elevación de 15 cm [2233.75 m.s.n.m.] sobre la corona [2233.6 m.s.n.m.], por lo que bajo este escenario se considera una cuenta con riesgo hidrológico. Además, se obtuvo que para una descarga controlada para un periodo de retorno de 10,000 años el área urbana afectada sería de 143 hectáreas, impactando aproximadamente a una población de 5,940 habitantes en el área de estudio.

Objetivos
Luvia extraordinaria
Simulación
Determinar áreas de inundación
Determinar acciones preventivas

Resultados:
El área urbana afectada sería de 143 hectáreas y una población de 5,940 habitantes en el área de estudio.

Contribuciones:
El desarrollo de modelos de predicción de zonas propensas a inundación a causa de lluvias extraordinarias.

Método

Obtención de datos
Topografía
Tipo de Vegetación
Tipo de Suelo
Propiedades Hidrológicas

Procesamiento
Lluvia-escurrimiento, a partir de los datos obtenidos.

Modelo
Lluvia escurrimiento
Hidrológico
Hidráulico
Hidrológico-Hidráulico integrado

Evaluación

Lluvia Máxima, Gasto, Inundación, Simulación

Area: Dissemination and universal access to science

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Introduction

The presence of rainfall in a specific region can have a favorable impact, allowing aquifers to recharge and increasing the storage volume in dams or reservoirs. However, when land use has changed from its natural behavior, mainly due to the construction of urban infrastructure, coupled with the duration, intensity, and number of rainfall events, these events have implications and impacts at the local scale, primarily due to the effect of disasters related to runoff processes and subsequent flooding [Gochis et al. 2006].

Extreme events can occur at different scales, and the effects are generally more significant at the local scale. Therefore, in a small watershed associated with its geomorphological characteristics, there may be a greater impact on the population [Pineda et al. 2014; Xinyue Gu et al. 2025]. Likewise, if an additional component is added to these events, namely the discharge from the dam located upstream of the population, The stream that crosses the town has a free spillway designed for a flood with a 10,000-year return period, and the hydraulic capacity of the stream that crosses the town has been reduced.

Northwestern Mexico is generally semi-arid, with an annual rainfall pattern dominated by the warm convective season that interacts strongly with the regional topography and surrounding water bodies [Gochis et al. 2006]. At the same time, stream and river beds have been degraded mainly due to urbanization. The construction of bridges and dams has caused an imbalance in flow, mainly in seasonal streams, causing sedimentation problems in major waterways [Pineda et al. 2014].

These phenomena render the natural channel insufficient during extraordinary rainfall events. Extreme precipitation events require an understanding of the conditions under which they occur. This is important, as it could lead to the development of flood warning systems for flood risk management [Pineda et al. 2014].

Likewise, alternatives can be designed to manage the flow, either through the natural channel or by building new canals that channel water to neighboring basins before reaching the population, minimizing the floodable area.

The factors that generate extraordinary rainfall events in northwestern Mexico are linked to large-scale mechanisms, such as the North American Monsoon System [NAMS, also known as the Mexican Monsoon] [Cavazos et al., 2008].

In the highland region of Zacatecas state, significant rainfall occurs in the summer, especially in the months of July, August, and September. Each extraordinary event represents a potential flood hazard due to the region's topography and the degraded conditions of the streambeds.

Historically, the plains have suffered from flooding. The population initially formed the higher areas less susceptible to flooding, but population growth, lack of land use planning, deforestation in the upper reaches of the watersheds, and a false concept of security associated with dam construction has made populations and productive areas very vulnerable [Arreguín et al. 2012]. The potential damage caused by large runoff events has reached historic economic levels, estimated at nearly 42.1 billion pesos in 2022, and these events affected the state of Zacatecas. Therefore, it is important to study the risk associated with extreme weather events, and numerical modeling is a useful and easy-to-implement technique in watersheds with insufficient information. However, for flood modeling, a desirable property is the ability to integrate hydrometric data, flood extent, and high-resolution terrain maps for operational applications [Bates and De Roo 2000].

The issue of flood model validation has been analyzed for both 1D and 2D models [Horritt and Bates, 2002]. In data-poor catchments, 1D models such as the Hydrologic Engineering Centers River Analysis System [HECRAS] have been shown to generate sufficient flood impact information even for large-scale events [Horritt and Bates 2002]. Limitations may also arise from a lack of data resources for validating numerical weather prediction [NWP] models such as radar gauges and rain-bucket models [Bates and De Roo 2000]. However, evaluation of single-event models is limited in terms of the verifiability of results, but can inform responsible authorities to take preventive actions that prevent flood risk from materializing or, where appropriate, to take preventive measures to evacuate the floodplain and thus avoid human losses.

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The advantage of using NWP is its ability to generate high-resolution data grids at many scales [Xuan et al. 2009].

The objective of the research was to simulate an extraordinary precipitation event in the Matamoros stream of the municipality of Calera de Víctor Rosales, Zacatecas, Mexico through the HEC-RAS 5.0 program in order to detect flooding areas for prevention.

Methodology

Area of interest

The state of Zacatecas is located between 21° 01' and 25° 07' north latitude and between 100° 43' and 104° 22' west longitude. It is made up of 58 municipalities [Figure 1]. It has an area of 75,275 km2, representing 3.8% of the Mexican Republic [eighth place in territorial extension]. It has a population of 1,622,138 inhabitants, representing 1.26% of the country's population [INEGI, 2020].

The municipality of Calera de Víctor Rosales has a population of 45,759 inhabitants, representing 2.80% of the state's population [INEGI, 2020]. Most of the municipality's territory belongs to the Fresnillo-Yescas Hydrological Basin of Hydrological Region No. 37 El Salado, is located in the central region of the state of Zacatecas south of the Tropic of Cancer, at 22°57' north latitude and 102°47' west longitude of the Greenwich meridian.

The average annual temperature of 16°C and an average rainfall of 500 mm, in the center where the municipality of Calera is located, the semi-dry climate and to the south the semi-humid, fits into the characteristics of the temperate semi-dry with a summer of irregular rainfall that can oscillate between 400 and 700 mm and a winter with occasional rains.

The maximum temperatures are recorded in the month of May, in the last three years they have exceeded 30°C and the minimum temperatures in January that can reach 4°C below zero. The prevailing winds flow from southwest to northwest and their action is accentuated from November to April.

Box 1

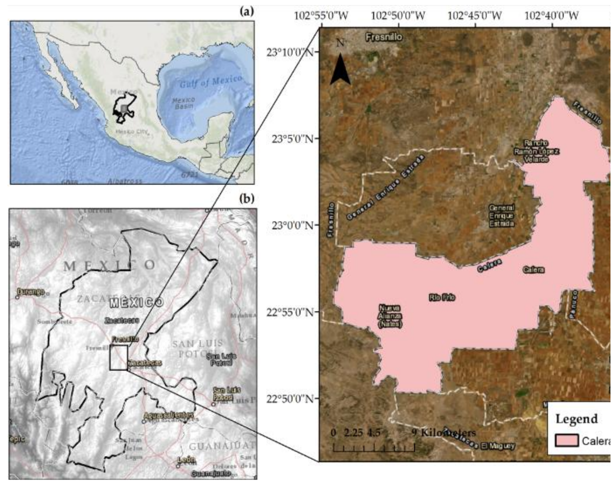

Figure 1
Study location

[by the authors]

The geological strata of the municipality of Calera are classified within the Quaternary period of the Cenozoic and Mesozoic eras.

Calera is located in the province of the Central Tableland and in the subprovince known as the Llanos and Sierra Potosino-Zacatecana. It is part of the alluvial plain located 2,000 meters above sea level that extends northward from Fresnillo to Cañitas de Felipe Pescador and southeastward to Calera de Víctor Rosales. Its floor is of caliche [petrocalcic horizon], with scattered mountain ranges and elongated strips called “bajíos” [shallows].

These “bajíos” contain deep soils mostly used for agriculture. In some ways, these “bajíos” can be considered water-collecting strips that, during the rainy season, have water reserves far exceeding those corresponding to precipitation. The municipality of Calera generally corresponds to the type of arid and semi-arid regions, and the varieties are gypsisols, which correspond to the ochric horizon, whose main characteristic is their lack of organic matter.

One of the types in the region is the luvic gypsisol, with a lithic bedrock and a thickness of 20 to 45 cm with medium texture. Another type of gypsisol has a bedrock of petrocalcic rock [caliche] with a medium texture and a thickness of 30 to 70 cm [commonly called red earth]. In smaller quantities than gypsisol, there are areas of yermosol, also of the ochric horizon.

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Another variety of soil found in Calera is the castañozem, which belongs to the mollic horizon, which is luvic without salinity; its bedrock is petrocalcic rock, has a medium texture, and its thickness ranges from 35 to 80 cm. There are also soils classified as pheozem, belonging to the mollic horizon with moderate productive potential. There are also strips of eutric lithosol with a thickness of approximately 10 cm. They have little productive potential and can only withstand very moderate grazing.

The Calera or Matamoros Stream originates on the border with the Santiago River Hydrological Region. Its main course runs south to northeast, crossing the urban area of Calera through the center. The watershed area is 47.98 km^2; the stream has an average gradient of 0.011%, with an elevation range between 2428.7 and 2227 m above sea level. Other streams form near this watershed and eventually discharge into the Sedano Lagoon.

Settlements located on the banks or near riverbeds are exposed to a high risk of flooding, depending on their proximity to the riverbed and the characteristics of their topography. Generally, the plains can generate floodplains, the severity of which will depend on the intensity of the rainfall that occurs in the catchment basins and how they can be regulated in the dams that are located upstream of the population. Considering this, the flows will be estimated for different return periods [Tr] and the flood scenario will be simulated for a Tr of 10,000 years.

Geomorphological and Topographic Characterization

Hydrologically, the basin functions as a large collector that receives precipitation and transforms it into runoff. This action is a function of a large number of parameters that influence the hydrological behavior of the basin. To date, it has been proven that some indices and characteristics influence the hydrological response of the basin [Campos Aranda, 1998].

They are the starting point for hydrological analyses of the basin [Table 1].

Box 2

Table 1

Hydrological features

Data	Parameter/equation	References
Compactness coefficient	$K_c = \frac{0.28\,P}{\sqrt{A}}$	Horton 1940. Viesman 1989, Lisley 1977
Elevation	MDE	Inegi, 2020
Channel length	MDE	Inegi, 2020
Elongation ratio	$R_e = 1.128\frac{\sqrt{A}}{L}$	Strahler 1957
Stream density	$F = \frac{\sum N_i}{A}$	Strahler 1957
Area [A]	A = Basin area [km^2]	Strahler 1957
Perimeter [P]	P = Basin perimeter [km]	Smith, K.G, 1957
Main channel length [Lc]	Lc = Length of main channel [km]	Horton 1940. Strahler 1957, Smith, K.G, 1957
Stream order [u]	u = Stream order [dimensionless]	Horton 1940. Strahler 1957, Smith, K.G, 1957
Total number of flow channels [Nu]	Nu = Number of flow channels	Horton 1940. Strahler 1957, Smith, K.G, 1957
Total channel length [Lu]	Lu = Length of all flow channels in the basin [km]	Horton 1940. Strahler 1957, Smith, K.G, 1957
Drainage density	$D_d = \frac{\sum l}{A}$	Horton 1940. Strahler 1957, Smith, K.G, 1957

It is called a topographic survey when the extension is topographic [less than 30 km] or geodetic [more than 30 km], they can be cadastral, they are carried out in urban areas, cities and municipalities to obtain the inventory of real estate, basis of property taxes and regulatory plans in this research a hydrographic survey was carried out, which allows to obtain the description and study of the different bodies of water such as oceans, lakes and rivers obtaining the configuration of the underwater terrain.

In this research the latter is used to generate cross sections of the stream bed equidistant every twenty meters [20] meters based on a UTM coordinate system, georeferenced, the longitudinal profiles along the axis of the stream must record the bottom of the channel, as well as both margins, detailed topographic plans must be obtained at a horizontal scale of 1:1000 and a vertical scale of 1:100, with contour lines equidistant every 0.50 m, covering an area of approximately half a hectare, or that area that allows the discharges to be delimited.

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Temporal rainfall series

The monitoring and recording of maximum rainfall over 24 hours is controlled by three climatological stations, with geographic coordinates [Table 2], which are managed by CONAGUA. These provide information on precipitation, temperature, relative humidity, evaporation and winds.

Box 3

Table 2

Climatologic stations of the Arroyo Matamoros´s basin

#	Station	Municipality	Latitude	Longitude	m.a.s.l. [m]
32003	Calera	Calera	22°54'30.96"	102°39'34.9"	2,097
32002	Boca del Tesorero	Jerez	22°49'25"	102°57'6"	2045
32173	El Peñasco	Gral Enrique Estrada	22°59'34.08"	102°50'13.9"	2,246

The annual historical data for the period [1989-2018], of the maximum 24-hour precipitation of the aforementioned stations are shown in Table 3.

Box 4

Table 3

Maximum 24-hour precipitation data [mm] for the Arroyo Matamoros watershed.

Year	Boca del Tesorero	Calera	El Peñasco
1989	39.5	39	-
1990	31.8	70.3	-
1991	48	57.5	-
1992	40	28.5	-
1993	49.4	30.4	-
1994	64	42	-
1995	51	31	-
1996	53.5	34.5	-
1997	25.6	30.8	-
1998	44.5	45.9	-
1999	34	33.7	-
2000	45.6	47	-
2001	32.9	37.5	-
2002	60	72	-
2003	60	36.8	36.3
2004	43.2	33.6	43.0
2005	29	27	30.7
2006	75.1	38.6	78.6
2007	40	39.2	30.3
2008	46.5	32	49.8
2009	43	56.2	35.0
2010	26.7	66.5	56.7
2011	31	52.2	25.0
2012	31.2	30.7	31.0
2013	55	45.4	55.0
2014	50.6	38.8	64.6
2015	55.7	46	69.0
2016	30.8	43	44.0
2017	32.4	29.4	45.5
2018	39.6	70.2	46.5

Design Expenditure

The conversion of precipitation to runoff will be carried out using the United States Soil Conservation Service [USDA] method, using the N curve number. This is a robust, acceptable, and simple method for determining excess rainfall after the infiltration process. It produces runoff in ungauged basins, both urban and non-urban.

This method determines the runoff coefficient using [Equation 1].

$$C = \frac{\left[P_{mc} - 508\left(\frac{1}{N} - \frac{1}{1000}\right)\right]^2}{P_{mc}\left[P_{mc} + 2032\left(\frac{1}{N} - \frac{1}{100}\right)\right]} 100. \qquad [1]$$

where P_{mc} is the average annual precipitation in centimeters and N is the runoff number or curve number.

To determine the N value, a specific combination of soils, vegetation cover and land use, hydrologic group, and antecedent moisture conditions [previous rainfall] will be identified. Hydrologic soil groups and N values will be determined using a combination of soil texture and vegetation cover [USDA, 2005]. A design precipitation and flow rate will be projected for a return period of 10,000 years. However, design precipitation will also be calculated using different hydrologic methods, and the one that best fits the watershed under study will be considered.

Flood Simulation

To simulate flooding due to peak rainfall, open-source software was used. HEC-RAS 5.0 is designed to perform one-dimensional hydraulic calculations for a complete network of natural and constructed channels. It is open-source software [https://www.hec.usace.army.mil/software/hec-ras/].

HEC-RAS 5.0 contains four one-dimensional analysis components for: [1] steady-flow water surface profile calculations; [2] unsteady-flow simulation; [3] moving-boundary sediment transport calculations; and [4] water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic calculation routines.

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In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are calculated.

Steady-flow water surface profiles are modeled for gradually varied flow. The system can handle an entire channel network, a dendritic system, or a single river reach. The steady-flow component is capable of modeling subcritical, supercritical, and mixed water surface flow regimes.

The basic calculation procedure is based on the solution of the one-dimensional energy equation [Table 4]. Energy losses are evaluated by friction [Manning's equation] and contraction-expansion [coefficient multiplied by the change in velocity head]. The momentum equation can be used in situations where the water surface profile is rapidly varied [Dávila, 2023].

Box 5

Table 4

2D Shallow Water Equations.

#	Equation
1	$\frac{\partial H}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=r$
2	$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -\frac{n^2 pg\sqrt{p^2+q^2}}{h^2}-gh\frac{\partial H}{\partial x} + pf+\frac{\partial}{\rho\partial x}(h\tau_{xx})+\frac{\partial}{\rho\partial y}(h\tau_{xy})$
3	$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) = -\frac{n^2 qg\sqrt{p^2+q^2}}{h^2}-gh\frac{\partial H}{\partial y} + qf+\frac{\partial}{\rho\partial x}(h\tau_{xx})+\frac{\partial}{\rho\partial y}(h\tau_{yy})$

where: H[x,y,t] = z[x,y] + h[x,y,t] is the surface elevation [m]; z is the cell elevation in Cartesian coordinates [x,y]; h is the water depth [m]; p=hu and q=hv are the specific flux in the x and y directions [m^2/s]; u and v are the velocities in x and y, respectively; r is the net rainfall [m]; g is the acceleration of gravity [m/s^2]; n is the Manning roughness coefficient [s/$m^{1/3}$]; ρ is the water density [kg/m^3]; τxx, τyy and τxy are the components of the stress tensor; and f is the Coriolis parameter [1/s]. The above equations are solved with an implicit finite volume scheme.

Results

Geomorphological Characterization

The Matamoros Creek flows through the town of Víctor Rosales, Zacatecas, Mexico. Its source is located at 2,227 meters above sea level, with geographic coordinates of 102° 46' 04.64" West, 22° 54' 59.15" North. It is located between the Mesa del Centro and the Sierra Madre Occidental, with a drainage area of 47.98 km². Its elevation varies from 2,227 to 2,428.7 meters above sea level, and its main channel is 18.34 km long [Figure 2]. According to the Chow 1982 classification, it is considered a small basin.

Box 6

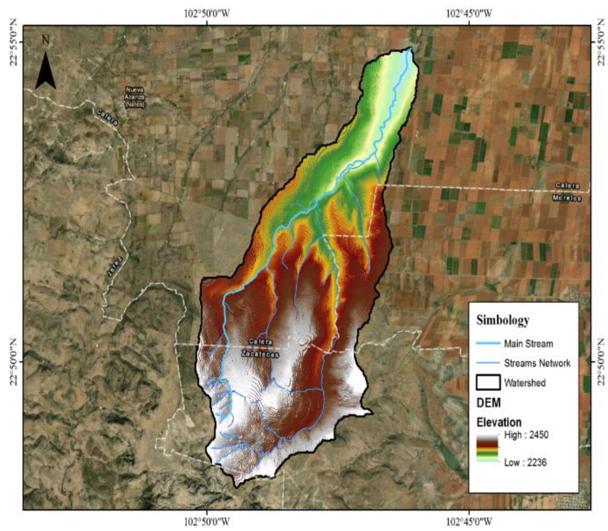

Figure 2

Arroyo Matamoros´s basin

The compactness coefficient was 1.41, indicating an elongated basin with high relief. The elongation coefficient of 0.41, with a slope of 0.011 to 0.019 m/m, is a mature basin, considering the hypsometric curve, indicating that the channels through which water flows are well-defined.

The predominant vegetation is agricultural-livestock-forestry with an area of 20.66 km^2; natural grassland 25.44 km^2; and Crassula scrub 1.88 km^2. This factor influences the rainfall-runoff relationship, as does the predominant soil type [lithosol and xerosol] [Figure 3]. Generally, this type of vegetation generates runoff rates ranging from 45 to 60.

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Box 7

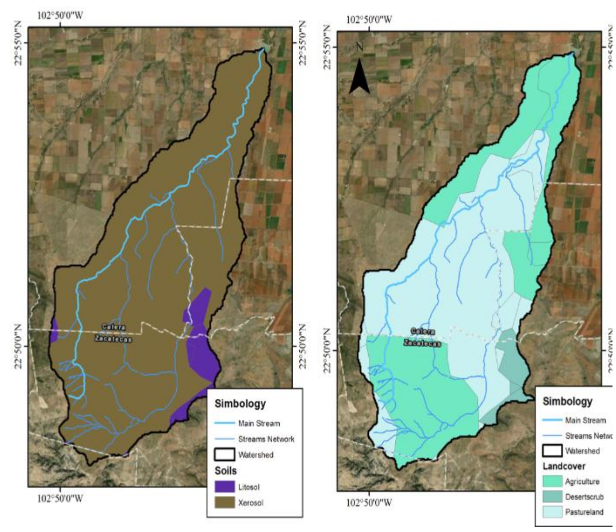

Figure 3

Vegetation and soil type

Determining the 24-Hour Maximum Rainfall

The maximum daily rainfall data were fitted to various probability distributions, considering the smallest standard error [Table 5]. The best distribution was the simple Gumbel, which was used to estimate the design rainfall for different return periods.

Box 8

Table 5

Probability distributions in Arroyo Matamoro´s basin

Boca del Tesorero		Calera		El Peñasco		Average	
μ =	42.919	μ=	40.5	μ=	44.333		
σ=	11.567	σ=	11.825	σ=	16.272		
γ=	0.698	γ=	0.809	γ=	0.805		
κ=	3.456	κ=	3.656	κ=	3.598		
10000	105	10000	128.69	10000	129.76	10000	117.44

For the intensity-duration-return period [I-D-Tr] curves, the Bell method [1969] was used. The I-D-Tr curves were generated based on the maximum rainfall data fitted with Gumbel [Table 6].

Box 9

Table 6

Intensity–Duration–Return Period of the weighted average of the basin stations.

Tr	Intensidad (mm/hr) - Duración (hr) - Periodo de Retorno														
	0.083	0.167	0.333	0.667	1	1.667	2	2.5	3	3.45	3.5	4	5	6	24
	Duración (min)														
	5	10	20	40	60	100	120	150	180	207	210	240	300	360	1440
5	137.9	103.2	71.98	48.1	37.48	27.08	24.06	20.78	18.41	16.77	16.61	15.19	13.06	11.54	4.402
10	163.2	122.1	85.18	56.92	44.36	32.05	28.47	24.59	21.79	19.85	19.66	17.97	15.46	13.65	5.209
20	188.5	141.1	98.37	65.74	51.23	37.01	32.88	28.4	25.16	22.92	22.7	20.76	17.85	15.77	6.016
50	221.9	166.1	115.8	77.4	60.31	43.57	38.71	33.43	29.63	26.99	26.73	24.44	21.02	18.56	7.082
100	247.2	185	129	86.22	67.18	48.54	43.12	37.24	33	30.06	29.77	27.22	23.41	20.68	7.889
200	272.5	203.9	142.2	95.04	74.05	53.5	47.53	41.05	36.38	33.14	32.82	30.01	25.81	22.79	8.696
500	305.9	228.9	159.7	106.7	83.14	60.07	53.36	46.08	40.84	37.2	36.85	33.69	28.97	25.59	9.763
1000	331.2	247.9	172.8	115.5	90.01	65.03	57.77	49.89	44.21	40.28	39.89	36.47	31.37	27.71	10.57
2000	356.4	266.8	186	124.3	96.88	70	62.18	53.7	47.59	43.35	42.94	39.25	33.76	29.82	11.38
5000	389.9	291.8	203.5	136	106	76.56	68.01	58.74	52.05	47.42	46.96	42.94	36.93	32.62	12.44
10000	415.2	310.7	216.7	144.8	112.8	81.52	72.42	62.55	55.43	50.49	50.01	45.72	39.32	34.73	13.25

Methods for Estimating Peak Flow

The rational method is probably the oldest model for the rainfall-runoff relationship, dating back to 1851 or 1889. Due to its simplicity, it is one of the most widely used. It assumes that the area studied receives uniform rainfall over a certain period of time, such that runoff in the basin is established and a constant discharge rate is achieved.

This method allows the determination of the maximum discharge caused by a storm, assuming that this is achieved when rainfall intensity is approximately constant for a certain duration, which is considered to be equal to the basin's time of concentration. The peak or maximum discharge is defined by [Equation 2].

Applying the rational method, the following design discharges are obtained [Table 7].

$$Q_p = 0.278CIA [2]$$

where Qp= Maximum or peak discharge, in m^3/s, C= Dimensionless runoff coefficient, I=Average rainfall intensity for a duration equal to the basin's time of concentration, in mm/h, A=Basin area, in km^2.

Box 10

Table 7

Peak flow designs applying the rational method [m^3/s].

Tr [years]	Chen	Kuishling	Bell
50	75.15	11.76	120.85
100	90.86	15.84	149.14
200	107.41	20.25	178.83
500	130.40	26.42	219.86
10,000	212.52	44.42	364.18

González-García, Cruz, González-Trinidad, Julián, Júnez-Ferreira, Hugo Enrique and Robles-Rovelo, Cruz Octavio. [2025]. Simulation of the flood zone for an extraordinary rainfall. Journal of Technological Engineering. 9[22]1-11: e2922111.
https://doi.org/10.35429/JTEN.2025.9.22.2.1.11

Mockus developed a synthetic triangular unit hydrograph. The peak discharge is obtained from its geometry or behavior using Equation 3:

$$q_p = \frac{0.556AP_e}{nT_p} \qquad [3]$$

where qp = Peak discharge of the unit hydrograph, in m^3/s-mm, A = Basin area in km^2, Pe = Effective precipitation [mm], n = Peak reduction factor, which is calculated using the following Equation 4:

$$n = 2 + \frac{A - 250}{1583.33} \qquad [4]$$

For basins with an area greater than 250 km^2, and n = 2 for basins smaller than 250 km^2. Tp = Peak time, equal to the time between the start and maximum of direct runoff in hours, calculated using Equation 5.

$$Tp = 0.5\,D + Tr \qquad [5]$$

where Tr is the return period and D = Duration of effective precipitation, considering D = tc.

The return time is estimated using the time of concentration tc, considering that Tr = 0.6tc. Therefore, the time to peak is calculated according to Equation 6:

$$T_p = 0.5D + 0.6 \qquad [6]$$

A discharge for a return period of 10,000 years is obtained using Chen's excess rainfall method: 193.20 m^3/s. When compared with the estimate using the rational method, there is a difference of 19.32 m^3/s. Some authors [Joko et al., 2022; Zeda et al., 2024] have found similar values; that is, the rational method reports higher values, which is why it has been recommended for small watersheds where urban use predominates.

Simulation models

The simulation was performed using the HEC-RAS 5.0 model. The model's geometry input data were obtained from topography processing in HEC-GeoRAS, and the flow data were obtained from the described models. The water surface profile is calculated by the simulator, which considers one section to the next by solving the Energy Equation [Equation 7] using an iterative procedure called the Standard Step Method [https://www.hec.usace.army.mil/software/hec-ras/features.aspx].

$$Z_2 + Y_2 + \frac{a_2V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1V_1^2}{2g} + h_c \qquad [7]$$

The HEC-RAS 5.0 model can hydraulically simulate the design flow rate considering a subcritical, supercritical, or mixed flow regime. The specific force equation is used in the model to determine which flow regime is the majority or controlling flow regime, as well as the location of any hydraulic jumps.

The equation for the specific force is derived from the momentum equation. For a very short channel reach, the external friction force and the force due to the weight of the water are very small and can be ignored [HEC-RAS 5.0 Reference Manual, 2015].

The momentum equation reduces to the following Equation 8:

$$\frac{Q_1^2\beta_1}{gA_1} + A_1\bar{Y}_1 = \frac{Q_2^2\beta_2}{gA_2} + A_2\bar{Y}_2 \qquad [8]$$

where: Q = flow rate at each section, β = momentum coefficient [similar to alpha], A = total flow area, Y = depth from the water surface to the centroid of the area, g = gravitational acceleration.

When the specific force is applied to natural channels, the equation reduces to Equation 9:

$$SF = \frac{Q^2\beta}{gA_m} + A_T\bar{Y} \qquad [9]$$

where A_m= Area of the flow in which there is movement. At= Total area of the flow, including ineffective flow areas.

The equation consists of two terms: the first term is the momentum of the flow passing through the channel cross section per unit time.

This part of the equation is considered the dynamic component. The second term represents the momentum of the static component, which is the force exerted by the hydrostatic pressure of the water.

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The sum of the two terms is called the specific force [Chow, 1959]. Mixed-regime calculations for steady-state flow analysis use the water surface in a subcritical regime based on known downstream boundary conditions.

During subcritical regime calculations, all locations where the model defaults to critical depth are flagged for further analysis.

The results generated through HEC-RAS 5.0, considering the calculated design flow rates and satellite remote sensing images, as well as field topography refinement, are presented below.

During the physical surveys, the physical characteristics of the channel material were observed, both at the bottom and on the banks and floodplains [Figure 3], in order to have elements to propose Manning coefficient values.

Box 11

Figure 3
Arroyo Matamoros´s basin

Hummel, Duan and Zhang [2012] in ephemeral channels in the state of Arizona in the United States of America compares the models for unsteady and semi-unsteady flow in the simulation with sediment transport and describes the way in which these models work with hydraulic simulation, recommends that the coefficients used for Semi-desert Zones be those referenced in Table 8 and Figure 4.

Box 12
Table 8
Simulation coefficients.

Manning coefficient		
Left	River	Right
0.04	0.036	0.04
Coeficients		
Expansion	0.3	
Contraction	0.1	

Box 13

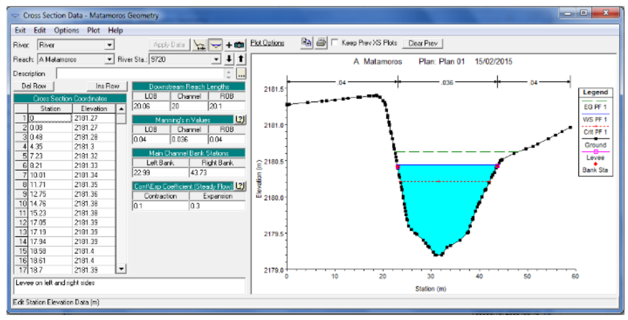

Figure 4
Coefficients used in Arroyo Matamoro´s simulation

With the modeling of the danger zones, it was obtained that for a controlled discharge with a return period of 10,000 years the affected urban area would be 143 hectares, which could affect 5,940 inhabitants of the municipality of Calera de Víctor Rosales, Zacatecas, Mexico [Figure 5].

Box 14

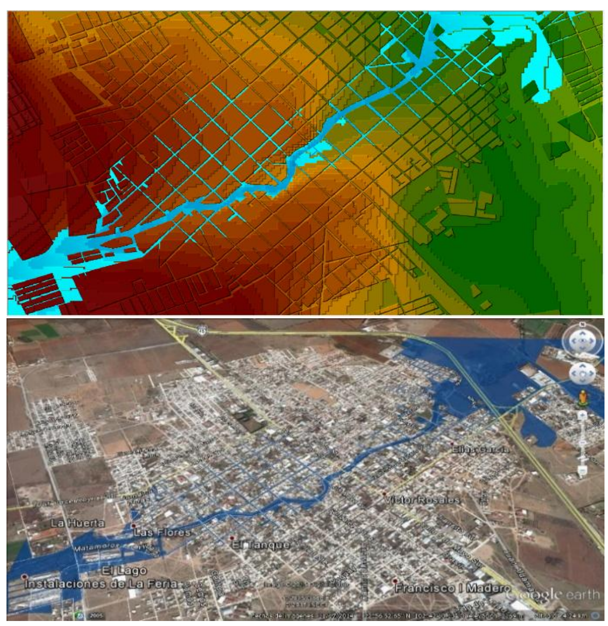

Figure 5
Determination of flood-prone areas in Calera de Víctor Rosales [View on Hec-Ras] and [View on Google Earth]

Conclusions

The extraordinary flooding in the reservoir, with a Tr of 10,000 years, resulted in an elevation of 15 cm [2233.75 m above sea level] above the crest [2233.6 m above sea level].

Therefore, under this scenario, the reservoir is considered a hydrological risk. Hazard zone modeling showed that, for a controlled discharge with a 10,000-year return period, the affected urban area would be 143 hectares, potentially affecting 5,940 residents of the municipality of Víctor Rosales.

Proposed risk mitigation actions:

By raising the dam by 1.00 m, the water level in the reservoir will be 0.85 m below the crest for a 10,000-year return period. This will prevent overflows that could cause failure of the graded material dam. The information obtained is used to plan the growth of urban areas, avoiding construction in floodplains.

Likewise, hydraulic conduction works, control structures, and communication structures must be designed to allow the residents of the municipal seat of Calera, Zacatecas, to live and move around safely in the face of adverse weather events.

Furthermore, the areas susceptible to flooding were identified, as well as the areas where greater care must be taken to expand their hydraulic section, in order to safeguard the physical integrity of the people living along the banks of the riverbed. Likewise, the data contained in this work allows for the evaluation of the hydraulic structures currently available in order to analyze their viability and plan any necessary works, such as the demolition and expansion of the area of street crossings, which would give better hydraulic performance to the channel that crosses the municipal head of Calera de Víctor Rosales, and also to line the entire stream with concrete at its crossing with the head, since with an area of 30 m^2, the flow that could pass through the crossings would be 120 m^3/s, whose flow corresponds to a return period of 500 years.

Declarations

Conflict of interest

The authors declare no interest conflict.

Author contribution

All authors contributed to the project idea, research method and technique.

Availability of data and materials

Further information could be requested to the main author.

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Prototype of an energy management system for a two-seater urban solar transport vehicle

Prototipo de gestión energética para auto solar biplaza de transporte urbano

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Abstract

This project begins with the design of an algorithm tailored to the functional needs of an intelligent energy management system for a two-seater solar vehicle. The algorithm is implemented in Python to simulate various operating scenarios and define the system's control logic. Based on the results, suitable hardware components—such as Raspberry Pi, Arduino, sensors, and actuators—are selected to meet system requirements. A device interconnection diagram is then created to represent the flow of energy and data, along with each component's role. The system aims to improve efficiency, ensure traceability, and promote sustainable electric mobility in Mexico, with potential for scalability and commercial application in urban and suburban contexts.commercial

Objective	Methodology	Contribution
Develop an intelligent energy management system for a solar two-seater vehicle, optimizing autonomy, traceability, and sustainability.	Development of the intelligent energy management system proposal through: Data acquisition, logical modeling, modular integration with HMI, and energy validation in controlled scenarios	Development of the foundational framework to establish a functional prototype of the energy management system in the solar two-seater vehicle

Sustainable Electric Mobility

Area: Dissemination and universal access to science

Resumen

Este proyecto inicia con el diseño de un algoritmo que responde a las necesidades funcionales del sistema inteligente de gestión energética para un vehículo solar biplaza. Posteriormente, se implementa en Python para simular distintos escenarios operativos y establecer la base del programa principal. A partir de los resultados obtenidos, se seleccionan teóricamente los componentes de hardware —como Raspberry Pi, Arduino, sensores y actuadores— que cumplen con los requerimientos del sistema. Finalmente, se elabora un diagrama de interconexión que representa el flujo de energía y datos, así como la función de cada dispositivo. El sistema busca mejorar la eficiencia, garantizar trazabilidad y fomentar la movilidad eléctrica sustentable en México, con potencial de escalabilidad y aplicación comercial.

Objetivo	Metodología	Contribución
Desarrollar un sistema inteligente de gestión energética para auto solar biplaza, optimizando autonomía, trazabilidad y sostenibilidad	Desarrollo de propuesta del sistema inteligente de gestión energética través de Adquisición de datos, modelado lógico, Integración modular con HMI, validación energética en escenarios simulados controlados	Desarrollo de las bases para establecer el desarrollo de un prototipo funcional del sistema de gestión energética en el vehículo solar biplaza

Movilidad Eléctrica Sustentable

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Introduction

This paper presents the development of a smart solar system for a two-seater vehicle, based on the design previously published in Journal Innovative Design [ISSN: 2523-6830].

The project aims to study materials and components that offer the right characteristics for prototype design and research development focused on energy efficiency and technological advancement.

The proposal will be applied to a two-seater solar car, intended for urban and suburban transport, as a sustainable and modern solution.

To implement the energy management system, capable of automatically optimising the use of solar energy and electrical storage, an algorithm will be analysed that covers both the behaviour of the system and the interconnection of the components responsible for executing the corresponding tasks.

Based on the information collected, a proposal for a functional and sustainable prototype will be developed, tailored to the needs of the two-seater solar vehicle for urban transport.

1. Background

In previous stages, the project began in August 2016 with the development of a single-seater solar car prototype for urban-suburban transport, designed to compete in the 'Chihuahua Solar Challenge, 2016 edition' [ISSN online: 2414-4827, ECORFAN]. Subsequently, in July 2017, a solar car competition was held at the Technological University of Northern Aguascalientes.

These activities led to peer-reviewed publications, and the project is currently being revived with the design of a final prototype of a two-seater solar car, based on a study conducted in 2024 which, using statistics and data from the solar car market, demonstrated public acceptance of the project [ISSN: 2523-6830, magazine published by ECORFAN-Mexico].

In this new stage, the aim is to analyse and develop an energy management system capable of automatically optimising the use of solar energy and the electrical storage system.

Justification

Given the growing momentum towards sustainable mobility and energy transition in the transport sector, the development of technological solutions applied to solar vehicles represents a priority line of action for institutions committed to innovation and sustainability, such as SECIHTI. In this context, the design of an electronic module for the energy management of a two-seater solar car not only responds to the technical challenges associated with the efficient use of solar energy, but also promotes capacity building in applied engineering, automation and electrical systems analysis.

The proposal is based on the need to integrate interdisciplinary knowledge—from the identification of functional requirements to the simulation and selection of components—that allows for the construction of viable and scalable solutions for urban and suburban environments. Likewise, the methodological approach guarantees the optimisation of the system's energy performance, contributing to the development of clean technologies and the strengthening of institutional strategies aimed at smart mobility.

This project is aligned with the research and technological development axes promoted by SECIHTI, as it encourages the practical application of scientific knowledge in real contexts, promotes innovation in the design of electro-electronic systems, and generates transferable knowledge for future initiatives in the field of self-sustainable mobility.

Considering the sustained growth in demand for environmentally responsible mobility solutions, the development of a two-seater solar vehicle prototype is proposed as a feasible and strategic alternative to the challenges presented by transport in urban and suburban areas of the country.

At the same time, the study explores the potential of incorporating photovoltaic technologies into the charging infrastructure for electric vehicles, highlighting both the technological advances and the operational limitations that must be addressed for their effective implementation.

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Problem Statement

How can a self-sustaining solar vehicle prototype be developed that guarantees mobility, efficiency and safety, responding to the global challenge of reducing emissions without relying on external energy infrastructure? Currently, there is a significant gap between the conceptual design of solar vehicles and the implementation of energy management modules that integrate photovoltaic technologies, power electronics and adaptive control algorithms.

This gap limits the autonomy, operational efficiency, and scalability of prototypes, hindering their practical application in real-world contexts. In this regard, the development of an energy management system that integrates with the solar car is required so that it is not only technically viable but also responds to the specific conditions of the Mexican environment, considering factors such as urban infrastructure, usage patterns, and the availability of solar resources.

The lack of integrated and validated solutions represents an obstacle to the advancement of solar mobility projects and raises the need to design, simulate and build an electronic module capable of optimising energy flow, ensuring compatibility between components and improving the overall performance of the vehicle

Research Hypothesis

Hypothesis 1

If an electronic energy management module is designed considering criteria of efficiency, compatibility and adaptability to the urban environment, then the use of solar energy in the two-seater vehicle will be optimised, improving its range and operational performance.

Hypothesis 2

If theoretical simulations and functional analyses are incorporated into the energy system component selection process, then it will be possible to develop a technically viable solution tailored to the specific conditions of the two-seater solar car.

Methodology

Step 1. The first step is to develop the algorithm that covers the needs and functionalities of the two-seater solar car's energy management system.

Step 2. To complement the algorithm, programming is carried out in Python programming software to simulate the possible behaviour of the system and establish the basis for the main programme of the energy management system.

Step 3. Once the results of the energy management system's behaviour are available, the necessary hardware elements that theoretically meet the system's requirements are analysed to complement the system and integrate a prototype proposal that would meet the requirements and needs of the energy management system.

Step 4. A device interconnection diagram is developed to interpret the order and function of each device considered in step 3.

4. Results

After conducting this research, the following results were obtained:

Step 1. As a first step, the algorithm covering the functional needs of the energy management system for the two-seater solar vehicle was developed. This algorithm includes the following stages:

1. Load data from the database.
2. Process variables such as average current, motor effort, and energy combination.
3. Encoding categorical variables.
4. Training a classification model based on decision trees.
5. Making predictions and updating the Excel file.
6. Implementing STRIPS-type symbolic logic.
7. Simulating 12 dynamic scenarios.
8. Displaying results in an interactive table.
9. Visualising predictions using interactive graphs.

The corresponding pseudocode is established as follows:

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1. Read Excel file with solar and battery voltage readings.
2. Calculate average current per block of 10 readings.
3. Evaluate motor effort [up, down, normal].
4. Determine initial combination [solar or battery].
5. Encode effort and combination.
6. Train decision tree model with processed data.
7. Predict optimal combination for each record.
8. Save updated Excel file with predictions.
9. For each of the 12 simulated scenarios:

a) Generate random values for solar voltage, battery voltage, and current.
b) Evaluate effort.
c) Code effort.
d) Predict optimal combination with the model.
e) Apply STRIPS logic to decide the energy source.
f) Save result.

10. Display table with the 12 simulated scenarios.
11. Generate scatter plots to visualise the predictions.
12. End.

Step 2. Programming was carried out in the Python environment to simulate the behaviour of the system and establish the basis of the main programme that will manage the energy in the two-seater solar vehicle.

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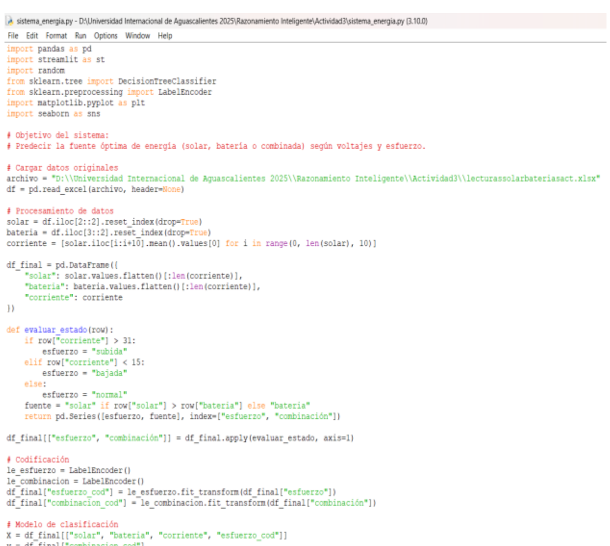
Box 1



```
sistema_energia.py - D:\Universidad Internacional de Aguascalientes 2025\Razonamiento Inteligente\Actividad3\sistema_energia.py (3.10.0)
File Edit Format Run Options Window Help
import pandas as pd
import streamlit as st
import random
from sklearn.tree import DecisionTreeClassifier
from sklearn.preprocessing import LabelEncoder
import matplotlib.pyplot as plt
import seaborn as sns

# Objetivo del sistema:
# Predecir la fuente óptima de energía (solar, batería o combinada) según voltajes y esfuerzo.

# Cargar datos originales
archivo = "D:\\Universidad Internacional de Aguascalientes 2025\\Razonamiento Inteligente\\Actividad3\\lecturassolarbateriasact.xlsx"
df = pd.read_excel(archivo, header=None)

# Procesamiento de datos
solar = df.iloc[2::2].reset_index(drop=True)
bateria = df.iloc[3::2].reset_index(drop=True)
corriente = [solar.iloc[i:i+10].mean().values[0] for i in range(0, len(solar), 10)]

df_final = pd.DataFrame({
    "solar": solar.values.flatten()[:len(corriente)],
    "bateria": bateria.values.flatten()[:len(corriente)],
    "corriente": corriente
})

def evaluar_estado(row):
    if row["corriente"] > 31:
        esfuerzo = "subida"
    elif row["corriente"] < 15:
        esfuerzo = "bajada"
    else:
        esfuerzo = "normal"
    fuente = "solar" if row["solar"] > row["bateria"] else "bateria"
    return pd.Series([esfuerzo, fuente], index=["esfuerzo", "combinación"])

df_final[["esfuerzo", "combinación"]] = df_final.apply(evaluar_estado, axis=1)

# Codificación
le_esfuerzo = LabelEncoder()
le_combinacion = LabelEncoder()
df_final["esfuerzo_cod"] = le_esfuerzo.fit_transform(df_final["esfuerzo"])
df_final["combinacion_cod"] = le_combinacion.fit_transform(df_final["combinación"])

# Modelo de clasificación
X = df_final[["solar", "bateria", "corriente", "esfuerzo_cod"]]
y = df_final["combinacion_cod"]
```

Figure 1

Python Program for Algorithm Simulation

Once the programming of the algorithm in Python has been completed, the program is run to observe the results obtained. The data generated by the simulations are then presented, including the predictions of the classification model, the application of the STRIPS symbolic logic and the interactive visualisation of the dynamic scenarios.

These results make it possible to validate the behaviour of the energy management system and to evaluate its capacity to optimise the use of solar energy in the two-seater vehicle:

Box 2

Sistema Inteligente de Energía Vehicular

Este sistema predice la fuente óptima de energía según voltajes y esfuerzo.

Datos procesados

	solar	bateria	corriente	esfuerzo	combinación	esfuerzo_cod	combinacion_cod	prediccion_cod	prediccion
0	43	17	22.9	normal	solar	0	1	1	solar
1	21	40	31.6667	subida	bateria	1	0	0	bateria

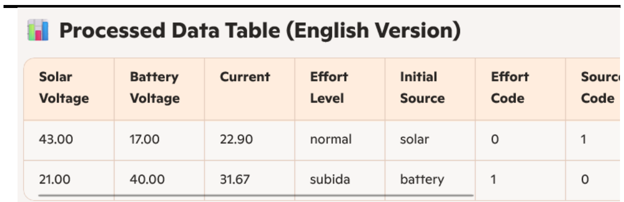
Figure 2

Sample of the result on screen

La tabla de datos procesados que se muestra en la Figura 2 representa el resultado del análisis preliminar del sistema inteligente de gestión energética, evidenciando las variables clave utilizadas en la simulación y entrenamiento del modelo de clasificación.

Box 3

Table 1



Processed Data Table (English Version)

Solar Voltage	Battery Voltage	Current	Effort Level	Initial Source	Effort Code	Sourc Code
43.00	17.00	22.90	normal	solar	0	1
21.00	40.00	31.67	subida	battery	1	0

Figure 3

Energy System – Processed Data Table

Description of columns in the processed data table

- Solar Voltage: Voltage measured directly from the solar panel system.
- Battery Voltage: Voltage measured from the vehicle's battery system.
- Current: Average current calculated from solar readings in defined blocks.

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- Effort Level: Symbolic classification of engine effort, coded as uphill, downhill, or normal.
- Initial Source: Initially selected energy source, determined by direct comparison of voltages.
- Effort Code: Coded numerical value representing the level of engine effort.
- Source Code: Coded numerical value representing the initial energy source.
- Prediction Code: Numerical output generated by the classification model [decision tree].
- Predicted Source: Final energy source recommended by the intelligent system, based on the model's prediction and symbolic logic.

The simulation section illustrates the response of the intelligent energy management system to 12 dynamic scenarios, generated using random values for solar voltage, battery voltage and current. In each scenario, the vehicle's effort level is evaluated — symbolically classified as downhill, uphill or normal — and an action based on STRIPS logic is applied, determined by comparing the available voltages. Subsequently, the trained classification model [decision tree] generates a prediction about the optimal energy source to use.

These results validate the system's ability to make autonomous and adaptive decisions under variable conditions, optimising energy flow and improving the operational performance of the two-seater solar vehicle.

Key observations:

Consistency between STRIPS and the classification model: In several simulated scenarios, the action determined by STRIPS symbolic logic coincides with the prediction generated by the classification model, demonstrating a functional alignment between the two approaches. For example, in scenario 0, both STRIPS and the model recommend using the battery as the energy source.

Informative divergences: In certain cases, such as scenario 1, STRIPS suggests the use of solar energy due to a higher recorded voltage, while the model predicts battery use. This discrepancy can be explained by the model's learning, which associates normal stress conditions and similar voltages with greater energy stability provided by the battery.

Predominance of the battery in predictions: In the 10 scenarios analysed, the model shows a tendency to favour the use of the battery, suggesting that it has identified patterns where this source is more reliable in the event of high stress or insufficient solar voltage.

Validation of the hybrid system: The coincidence between STRIPS and the model in multiple scenarios reinforces the validity of the energy management system. The divergences, on the other hand, open up opportunities to adjust the symbolic rules or enrich the model's training set, thus improving the system's adaptive capacity.

Box 4

Simulation of Scenarios – English Version

Solar Voltage	Battery Voltage	Current	Effort Level	STRIPS Action	System Prediction	Final State
10.23	12.76	12.42	downhill	use_battery	battery	battery
13.73	10.42	29.19	normal	use_solar	battery	solar
12.32	11.81	33.38	uphill	use_solar	battery	solar
13.57	11.23	31.74	uphill	use_solar	battery	solar
10.64	11.83	30.48	normal	use_battery	battery	battery
11.18	13.83	34.91	uphill	use_battery	battery	battery
12.47	11.75	32.66	uphill	use_solar	battery	solar

Figure 4
Results of Simulation of Scenarios.

Column Descriptions

Solar Voltage: Voltage measured from the solar panel system, representing the available solar energy.

Battery Voltage: Voltage measured from the battery system, indicating the stored energy capacity.

Current: Average current used to estimate motor load and energy demand.

Effort Level: Symbolic classification of vehicle effort according to terrain conditions [uphill, downhill, normal].

STRIPS Action: Decision on the energy source, derived from symbolic logic rules based on voltages and effort.

Arellano-Yáñez, Ricardo, Moreno-Granados, Tomas, Ortiz-Negrete, Carmela and Calvillo-Valdez, Oscar Daniel. [2025]. Prototype of an energy management system for a two-seater urban solar transport vehicle. Journal of Technological Engineering. 9[22]1-10: e3922110.
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System Prediction: Energy source recommended by the classification model trained through machine learning.

Final State: Energy source resulting from applying STRIPS logic, used to validate or contrast with the system prediction.

Visualisation of forecasts

Graph: Solar vs Battery by Prediction

Box 5

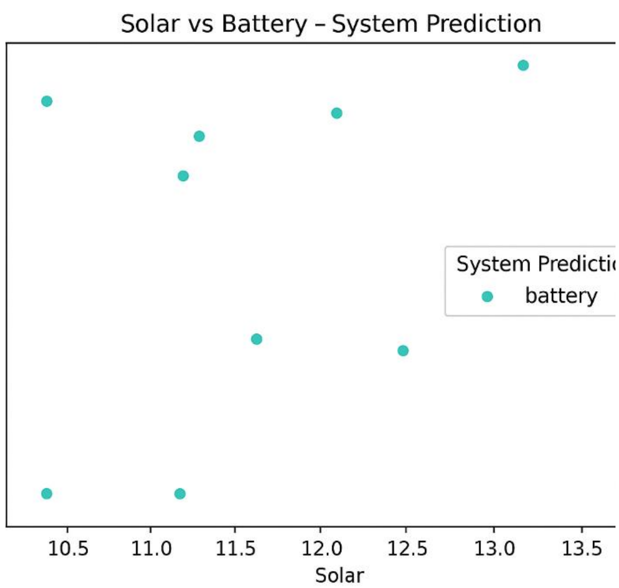

Figure 5
Solar vs Battery – System Prediction

- **Title**: *Solar vs Battery Voltage – System Prediction*
- **X-axis**: *Solar Voltage*
- **Y-axis**: *Battery Voltage*
- **Legend**: *System Prediction – Batter*

Interpretation of the energy decision graph
What does it represent?

The graph shows how the intelligent energy management system makes decisions about the energy source based on solar and battery voltages. Each point represents a simulated scenario, and the colour indicates the classification model's prediction. In this case, all points are labelled "battery".

Technical interpretation

X-axis [Solar]: Voltage available from the solar panel system.
Y-axis [Battery]: Voltage available from the battery system.

Colour: All points are classified as 'battery', indicating that the model considers this source to be more suitable in the scenarios represented.

Observations

Although some points have a higher solar voltage than battery voltage, the system still recommends battery. This suggests that the model has learned that, under certain conditions—such as high effort or similar voltages—the battery offers greater reliability.
• The dispersion of points indicates that the decision does not depend solely on which voltage is higher, but on how it relates to other variables such as average current and vehicle effort level.

Graph: Current vs. Battery according to Prediction: [Figure 6]

Box 6

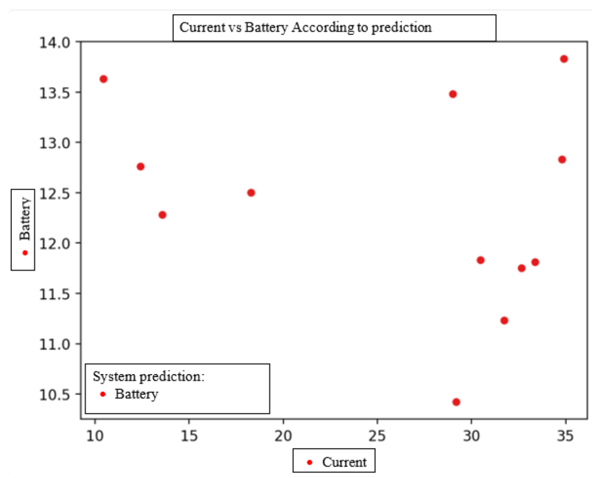

Figure 6
Current vs Battery According to prediction

¿ What does it represent?
Interpretation of the graph: Current vs.

Battery voltage

General description

The graph shows how the intelligent energy management system determines the energy source based on the motor current and battery voltage. Each point represents a simulated scenario, and the colour indicates the model's prediction. In this case, all points are classified as 'battery'.

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Article

Technical interpretation

- X-axis [Current]: Represents the motor effort. High values indicate higher energy demand, typically associated with uphill conditions.
- Y-axis [Battery Voltage]: Voltage available in the battery system.
- Colour: All points are labelled 'battery,' indicating that the model considers this source more reliable in the simulated scenarios.

Observations

- As the current increases, the system continues to recommend the battery, even when its voltage is not the highest.
- This suggests that the model has learned that, under high loads, the battery offers greater operational stability than the solar source.
- The dispersion of points shows that the decision does not depend solely on voltage, but on its relationship with variables such as engine load, which reinforces the adaptive nature of the system.

Graph: Current vs Solar Voltage – System Prediction: [Figure 7]

Box 7

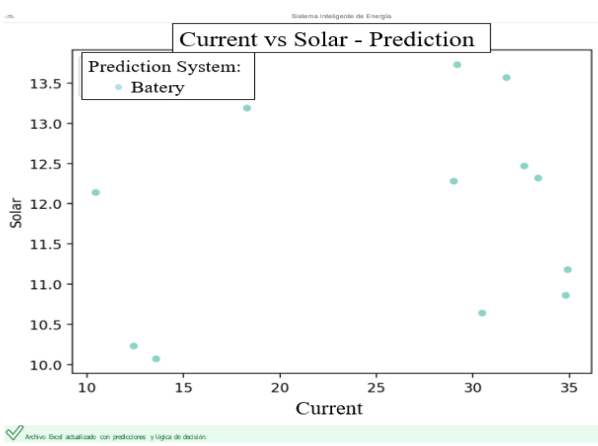

Figure 7

Current vs Solar According to prediction

- **Title:** ***Current vs Solar Voltage – System Prediction***
- **X-axis:** ***Current***
- **Y-axis:** ***Solar Voltage***
- **Legend:** ***System Prediction – Battery***

What does it represent?

This graph shows how the intelligent system decides on the energy source based on the motor current and the available solar voltage. Each point represents a simulated scenario, and the colour indicates the classification model's prediction. In this case, all points are labelled "battery", indicating that the system considers this source to be more reliable in the scenarios represented.

Technical interpretation

- X-axis [Current]: Represents the motor's effort. Higher currents indicate greater energy demand, such as when climbing a slope.
- Y-axis [Solar Voltage]: Voltage available from the solar system at that moment.
- Colour: All points are classified as 'battery', suggesting that the model prioritises this source for its stability.
- **Observations**
- Although some scenarios present relatively high solar voltages, the system continues to recommend battery as the main source.
- This indicates that the model has learned that, in the face of high effort [high currents], solar energy may not be sufficient or stable, so battery use is prioritised.
- The dispersion of points shows that there is no direct linear relationship between current and solar voltage in decision-making, which validates the use of a non-linear classification model such as the decision tree.

Step 3: Modular hardware proposal

Once the results of the energy management system's behaviour were obtained, an analysis was carried out of the hardware components that, in theory, meet the functional requirements of the system. This analysis made it possible to integrate a prototype proposal that meets the operational and technical needs of the intelligent energy management system.

Hardware suggested by function

Energy sensing

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Voltage sensor: INA219 or analogue voltmeters with resistive divider

Current sensor: ACS712 or INA226

Temperature sensor: LM35 or DHT22
Processing and control

Microcontroller: Arduino Mega or ESP32 [with Wi-Fi connectivity]

Embedded computer: Raspberry Pi 4 with Python environment and Streamlit visualisation
Proposed interconnection
Arduino: responsible for sensing and physical control

Raspberry Pi: executes the classification model and STRIPS logic

Communication: UART, I2C or Wi-Fi [if using ESP32]
HMI [Human-Machine Interface]

Touchscreen: Nextion 4.3‘ or 7’ to display voltages, stress and prediction

Alternative: 20x4 LCD with push buttons for basic navigation

Actuators and switching

Power relays: 30A relay module or SSR to switch between solar source and battery

Charge controller: MPPT compatible with feedback to Arduino

Power and protection

Fuses and protections: for system safety

DC-DC converter: to adapt voltages to Arduino and Raspberry Pi

Battery bank: energy storage

Solar panels: primary energy source

System logic integration

1. Arduino measures voltages, current and effort → sends data to Raspberry Pi
2. Raspberry Pi runs the ML classification model → sends decision to Arduino
3. Arduino activates relays according to STRIPS logic
4. HMI displays system status and allows user interaction

Step 4: Interconnection diagram

A device interconnection diagram was developed to interpret the order, function and flow of information between the components considered in step 3. This diagram facilitates the physical implementation of the system and ensures the traceability of each module within the prototype.

Box 8

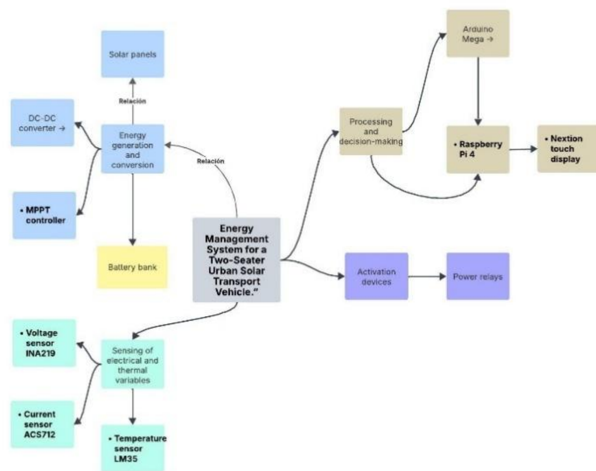

Figure 8
Interconnexions Diagram
Order of interconnection of elements

1. **Energy generation and conversion**

Solar panels → generate electrical energy from solar radiation.

MPPT controller → regulates the charge from the solar panels to the battery bank, maximising energy efficiency.

Battery bank → stores the energy regulated by the MPPT.

DC-DC converter → adapts the output voltage of the battery bank to power the vehicle's electronic systems.

2. **Sensing of electrical and thermal variables**

Voltage sensor INA219 → measures the voltage and current of the solar system or battery.

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Current sensor ACS712 → measures the motor current, useful for estimating the vehicle's effort.

Temperature sensor LM35 → measures the ambient or internal temperature, useful for thermal protection and charging decisions.

All these sensors are connected directly to the **Arduino Mega**, which acts as a data acquisition unit.

3. Processing and decision making

Arduino Mega → receives data from the sensors, processes it and sends it to the **Raspberry Pi 4**.

Raspberry Pi 4 → runs the classification model [machine learning] and determines the optimal energy source [solar or battery].

Nextion touch display → receives the decision from the Raspberry Pi and displays it to the user in real time.

4. Actuation

Power relays → receive control signals from the Arduino or Raspberry Pi to switch between energy sources according to the system's prediction.

5. Summary flow:

Energy: Panels → MPPT → Batteries → DC-DC → System

Sensing: Sensors → Arduino Mega

Processing: Arduino → Raspberry Pi → Display

Actuation: Raspberry/Arduino → Relays → Energy switching

Conclusions:

The intelligent energy management system for a two-seater solar vehicle will be developed by integrating symbolic decision algorithms and classification models based on machine learning, with the aim of efficiently predicting the optimal energy source according to operating conditions.

Simulations in Python and the visualisation of results have made it possible to validate the consistency between the STRIPS logic and the trained model. Subsequently, with the analysis of the hardware components necessary for physical implementation, those that meet the functional requirements of the system have been selected.

The interconnection diagram will establish a clear modular architecture, ensuring traceability between generation, sensing, processing and action, and laying the foundations for a functional prototype aligned with criteria of efficiency, sustainability and intelligent control.

Declarations:

Conflict of interest

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

Contribution of the authors

Arellano-Yáñez, Ricardo, the contribution to this article has been the original idea of the topic, as well as the direction and technical supervision of the research on the topic of this article.

Tomas Moreno Granados, Gerardo Méndez Macías, Carmela Ortiz Negrete, and Oscar Daniel Calvillo Valdez, co-authors of this article, contributed to the technical supervision, investigation of information sources, and writing of this article based on the research carried out.

Availability of data and materials

At this time, only the previous publications that have served to continue this research are available. The final results or those generated during the course of this research will be available in the corresponding publication of this article, as it is currently being developed and is now in the stage of characterising the proposed energy management prototype for a two-seater solar-powered urban transport vehicle.

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Abbreviations

UTNA: Technological University of Northern Aguascalientes References

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Background

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Journal of Technological Engineering 9[22]1-8: e4922108

Article

Green wall design for rainwater harvesting for human consumption

Diseño de muro verde para la captación de agua de lluvia para consumo humano

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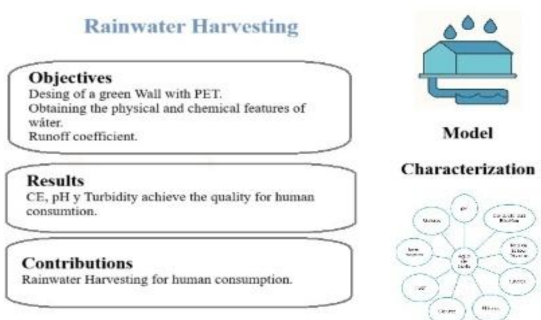
Abstract

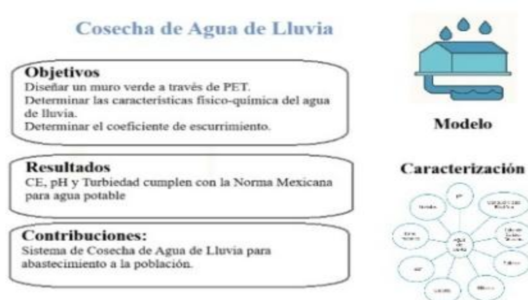
Water is expected to become one of the main issues of conflict throughout the 21st century. These scenarios are no longer a thing of the future. Currently, large cities, where an estimated two-thirds of the world's population lives, require large volumes of drinking water to meet their needs. Rainwater harvesting can become an alternative to reduce pressure on traditional sources. It is considered the cleanest natural source available and can be easily used and consumed both domestically, commercially, and industrially. This research aims to design a green wall through PET and considering the physical and chemical characteristics of rainwater. Recycled bottles and easily available materials are used, and it is connected to a harvesting system made of concrete and galvanized sheet metal. The parameters evaluated to determine water quality are physical characteristics [odor, color, turbidity], chemical [pH, EC, and hardness], and heavy metals. Most comply with Mexican and World Health Organization standards.



Rainfall Harvest System, Green Wall

Resumen

Es previsible que el agua se convierta en uno de los principales temas de conflicto a lo largo del siglo XXI este siglo, estos escenarios ya no son cosa del futuro actualmente las grandes ciudades donde se estima que viven dos tercios de la población mundial, requieren de grandes volúmenes de agua potable para satisfacer sus necesidades, la cosecha de agua de lluvia se puede convertir en una alternativa para disminuir la presión en las fuentes clásicas, se considera la fuente natural más limpia disponible y puede ser fácilmente usada y consumida tanto doméstico, comercial e industrialmente. Esta investigación tiene como objetivo diseñar un muro verde a través de PET y considerando las características físico – química del agua de lluvia. Se utilizan botellas recicladas y material de fácil adquisición, se conecta a un sistema de cosecha de concreto y lámina galvanizada, los parámetros que se evalúan para determinar la calidad del agua son características físicas [olor color turbiedad] química [pH, CE y dureza], además de metales pesados, la mayoría cumple con la norma mexicana y de la organización mundial de salud.



Cosecha De Agua De Lluvia, Muro Verde

Area: Dissemination of and universal access to science

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Introduction

Since humanity decided to settle in a place throughout its history, water has been a vital resource in addition to being an important factor for the growth of great cultures, cities, even countries, but the fact that it is always present has led to not giving it the importance it really has, because of that, the details that make the presence of the liquid possible have been neglected. According to studies that have been carried out prior to the year 2025, it was estimated that 3 million people could lack the basic requirements of vital water [González et al. 2023; Vele, et al 2024]. Likewise, water is expected to become one of the main issues of conflict throughout this century. However, these scenarios are no longer a thing of the future.

Currently, large cities, where an estimated two-thirds of the world's population lives, require large volumes of drinking water to meet their needs. To do so, they turn to surface and groundwater sources located at great distances, generating strong social conflicts among residents affected by the hydraulic works they generate. Urban areas are estimated to receive a quarter of the world's annual rainfall [Alvarado, 2017; Chubaka, et al., 2018; Nandgude, et al., 2023].

For this reason, rainwater harvesting can become an alternative to reduce pressure on traditional sources. It is considered the cleanest natural source available and can be easily used and consumed domestically, commercially, and industrially [Qianqian Zhang et al., 2014; Fernandes, Terêrencio and Pacheco, 2015].

Rainwater harvesting is considered an important technological option for the sustainable management of water intended for cities [Moglia et al., 2016]. Its use in buildings has been used worldwide for years and can be used as drinking and non-drinking water [Stec & Kordana, 2015].

The importance of this vital liquid has led to research leading to new discoveries in its use, seeking sustainability. Scientific reports agree that "rainwater harvesting is a strategy and alternative source for water use in places where it is scarce" [Matos et al., 2015]. These were used by pre-Hispanic cultures. The Mayans used the so-called "Chultunes" to provide water during the dry season.

In Mesoamerica, these practices have been common since ancient times. In the Mediterranean and Middle East, the system was already used by the Mesopotamians and widespread by the Greeks and, especially, the Romans throughout the region. The Arabs continued to use it.

On the other hand, the increase in air and soil pollution, deforestation, chemical use, and the destruction of fauna and flora are human activities that have currently endangered the continuity of the water cycle, making the process increasingly difficult. To obtain it and be able to bring it to everyone who needs it, it is therefore necessary to generate scientific knowledge using technological advances to offer new paths to obtain it.

This research proposes designing a green wall that stores rainwater through the roofs of houses or even buildings, in the city of Zacatecas and rural communities, as an alternative source of drinking water in urban housing in the city of Zacatecas in order to take advantage of rainwater for human activities. The objectives of this work are a] to characterize the homes by evaluating precipitation, catchment area, runoff coefficient; b] to design a green wall through PET; and c] to determine the physical and chemical characteristics of rainwater.

Methodology

The state of Zacatecas is located between the coordinates 22° and 23° North latitude and 102°-103° West longitude, it has a territorial area of 75,484 km^2; divided into 58 municipalities [Figure 1], it has a population of 1,622,138 [INEGI, 2020], the conurbation area called Zacatecas-Guadalupe where the green wall was developed and installed, has a population of 450,000.00 inhabitants and the community of Malpaso Villanueva, Zacatecas with coordinates 23 ° 37'30.83 "N 102 ° 36'20" W.

The city of Zacatecas [22 ° 44' 58.37 "N 102 ° 34' 52.99" W], has an average rainfall record of 502 mm per year and Malpaso 428 mm during the last 30 years. The population at the last analysis point is approximately 10,000 inhabitants.

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Box 1

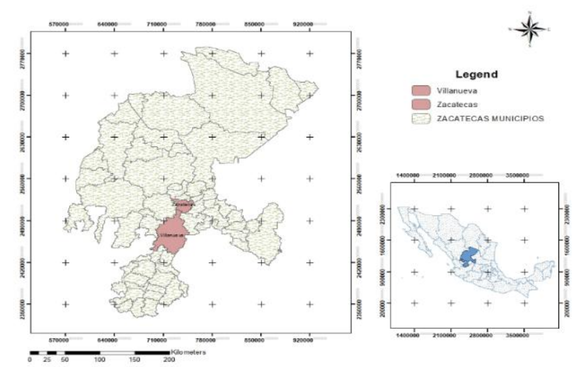

Figure 1
Study area location

Obtaining the water demand

Demand or supply per capita is the amount of water a person needs daily to fullfill their physical and biological functions. Therefore, its estimate is based on the number of inhabitants who will benefit from the rainwater harvesting system [Garduño and Martinez, 2007]. The mathematical expression for calculating water demand is as follows:

$$Dj = \frac{Nu * Dot * Ndj}{1000} \quad [1]$$

$$D_{anual} = \sum_{j=1}^{n} D_j * 12 \quad [2]$$

where D_j = water demand in month j, m^3/month/population; Nu = number of system beneficiaries; Dot = water supply, in l/person/day; Nd = number of days in month j; D_{anual} = water demand for the population; J = number of months [j = 1, 2, 3,…, 12]; 1000 = conversion factor for litters to m^3.

Net rainfall calculation

The efficiency of rainwater harvesting depends on the runoff coefficient of the catchment area materials, which ranges from 0.3 to 0.9 according to the literature [Zhou et al., 2023].

Equation [3] is used to estimate net precipitation:

$$PNijk = Pijk * \eta\ captacion \quad [3]$$

where:
PNijk = net precipitation for day i, month j, and year k, [mm], Pijk = total precipitation for day i, month j, and year k [mm], η capture = rainwater harvesting efficiency, 0.765.

The PN criterion is that when average monthly rainfall is less than 50 mm and of low intensity [mm/hr], it is recommended not to consider it, especially if it occurs during dry seasons, since the quantity and quality of the rainwater will not be considered for storage.

Calculation of volume of rainfall to collect

The rainwater catchment area is obtained using equation [4]

$$A = a\ x\ b \quad [4]$$

where A= Catchment area [m^2], a= Width of the house [m], b= Length of the house [m]

If the catchment area [SCALL] does not exist, it will be designed based on the annual demand of the inhabitants to benefit and the annual net rainfall [Equation 5]:

$$Aec = D_{annual} \sum_{J=12}^{n} \bar{P} \quad [5]$$

where Aec= is the catchment area needed to supply the water demand of a family or community [m^2], D annual= annual water demand needed by a population, $\bar{P}$ = sum of the average monthly net rainfall that causes runoff [mm], j= Number of rains in the month, j=1,…,12.

Green Wall Design [PET]

The green wall design will be made with materials such as PET [plastic bottles], PVC pipes, and an aluminium structure to help support the bottles [Figure 2]. The PVC pipes will serve as a pipeline to convey the water to the bottles, where it will be stored for later use. The PVC pipes can vary in size, as they will be adjusted to suit the bottles used.

Box 2

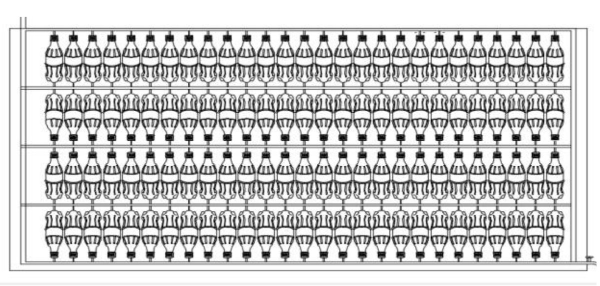

Figure 2
Green Wall Desing

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To increase the rainwater collection volume, the green wall is connected to a 10,000 to 50,000-liter cistern. This cistern is made of ferro-cement [Figure 3], but a high-density polyethylene [HDPE] cistern can also be adapted.

Physical-Chemical Analysis of Collected Rainwater

Water quality assessment is a multi-pronged process that studies the physical, chemical, and biological nature of water in relation to its natural quality, human effects, and aquatic health. Analysis of any water reveals the presence of gases, minerals, organic elements in solution or suspension, and pathogenic microorganisms.

The physical analysis of the samples was performed in the Hydrogeochemical Laboratory of the Electrical Engineering Academic Unit to obtain data and compare them with the guidelines of the Mexican standard NOM-127-SSA1-1994, modified in 2021, and the [*World Health Statistics 2022*, s/f] standard for human consumption [Table 1].

Box 3

Table 1

Analysis methods and maximum permissible limit

Physical parameter	Reference	Permissible limit in Mexico[mg/l]	Permissible limit WHO [mg/l]
Odor	APHA, 2020	Odorless	Odorless
Taste	APHA, 2020	Ok	Ok
True Color	APHA, 2020	15 [UC]	15
Turbidity		4.0 [UNT]	4.0
Chemical Parameters			
pH	APHA, 2020	6.5-8.5	
Electrical Conductivity [µS/cm]	APHA, 2020	700	700
Hardness [CaCO3]	APHA, 2020	500	500
Alalinity	[NOM-AA-036-SCFI-2001,]	300	300
Chlorides	[NOM-AA-073-SCFI-2001]	250	150
Nitrates [N-NO3]	APHA,2020	10	
Sulfates	APHA, 2020	400	400
Sodium	APHA, 2020	200	
Heavy Metals			
Iron	APHA, 2020	0.3	0.2
Zinc	APHA, 2020	3.0	2.0
Lead	APHA, 2020	0.01	0.01
Mercury	APHA, 2020	0.006	0.006
Arsenic	APHA, 2020	0.025	0.01

Results

According to the research objectives, the following results were obtained and discussed in relation to the work reported in the literature.

Housing Characterization

The aim is to adapt the regulations, designs, and shapes of current homes to capture a large amount of rainwater. This will allow them to meet the water demand of each user, thus generating a 90% utilization of the collected water.

This will reduce dependence on the drinking water network by three to four months. This will help reduce the volume of extraction from both surface and underground storage sources, and will also prevent rainwater contamination as it travels through the streets.

The rainwater collection area varies from 60 to 200 m^2 in the different strata [neighborhoods and subdivisions] that make up the urban area of Zacatecas City and the community of Malpaso, part of Villanueva, Zacatecas.

Determining Demand

To determine the demand for a typical house with 4 people [the number of inhabitants per house ranges from 2 to 6], based on a supply of 50 litters/inhabitant/day, the minimum requirement is estimated to be 100 liters/inhabitant/day [*World Health Statistics 2022*, s/f].

However, due to differential rainfall patterns, it is necessary to estimate that for future generations, the requirement should be adapted to 50 liters per inhabitant to ensure the sustainability of the population's activities, especially where rainfall is very low, also considering an average of 30.4 days per month. The demand is therefore:

$$Monthly\ d = \frac{4 * 50 * 30.4}{1000} = 6 \frac{m^3}{month}$$

$$Annua\ d = 6\, m^3 * 12 = 72\, m^3$$

It is estimated that water consumption in the so-called working-class neighborhoods is 10 m3/month for a household with 4 inhabitants.

Therefore, if 72 m3 is collected, there would be a period of approximately 7 months where water would not be consumed from the drinking water network.

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It should be noted that the majority of the population of Zacatecas City does not drink water directly from the tap, but instead purchases jugs from water treatment plants.

A good percentage of the Malpaso community does drink water from their network, but some boil it before drinking it.

Net Precipitation

To determine monthly precipitation, it is necessary to analyze the climatological stations that cover the study area. This study considers the Malpaso and Zacatecas stations [Table 1 and 2] for the period 2009-2019. The data in red were estimated using the rational method, and monthly records are available.

Box 4

Table 2

Weather station in Zacatecas [2009-2019]

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
2009	0.0	0.0	10.0	5.0	10.0	86.3	72.0	126.3	88.3	30.5	53.0	21.5
2010	24.0	101.0	0.0	0.0	1.8	20.3	211.3	29.0	**18.5**	**17.5**	**4.8**	**0.0**
2011	0.0	0.50	0.0	0.4	1.2	1.4	88.3	51.8	81.6	21.7	0.0	0.0
2012	**6.2**	**17.5**	**2.5**	**0.0**	**2.9**	24.8	79.9	53.9	46.9	7.5	3.0	0.0
2013	**21.3**	0.0	0.0	0.0	14.2	42.9	33.1	72.7	197.2	57.5	20.3	82.8
2014	10.8	0.0	1.6	0.0	23.1	78.8	66.6	107.8	111.4	8.6	19.4	22.0
2015	24.1	51.1	120.5	25.3	47.9	245.5	155.8	66.6	134.2	115.1	14.2	18.7
2016	6.0	11.4	17.6	0.0	7.5	55.0	85.7	147.9	58.2	21.7	21.5	3.1
2017	0.0	0.0	4.8	10.0	5.9	20.6	216.3	186.0	108.6	25.3	0.0	16.3
2018	55.8	18.0	0.0	3.0	35.6	251.0	82.0	83.5	121.5	24.7	43.0	6.5
2019	12.0	0.0	4.5	0.0	**25.6**	36.3	66.6	79.0	120.8	43.3	**0.0**	**0.0**
MAX	**55.8**	**51.1**	**120.5**	**25.3**	**47.9**	**251.0**	**216.3**	**186.0**	**197.2**	**57.5**	**53.0**	**82.8**

According to [Garduño, 2011], precipitation greater than 40 mm must be taken into account, since lower values are not stored and the water is used to clean the catchment area.

This research also considers the season of maximum rainfall, since some winter months have rain, but with a very small frequency interval; therefore, the months of June, July, August, September, and October are included.

Box 5

Table 3

Weather station in Malpaso [2009-2019]

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
2009	0.0	0.0	0.2	5.0	7.7	94.9	97.3	88.5	74.7	50.2	71.7	29.1
2010	36.2	91.6	0.0	0.0	0.0	27.3	48.5	52.6	**56.0**	0.0	0.0	0.0
2011	0.0	0.0	0.0	0.0	0.7	95.9	34.7	21.3	117.5	20.2	0.0	0.0
2012	0.7	17.2	0.0	0.0	0.0	26.3	40.1	30.2	89.7	13.0	0.0	0.0
2013	3.5	0.0	0.0	0.0	0.0	4.9	166.2	10.9	196.1	78.2	3.6	53.1
2014	9.5	0.0	0.0	0.0	30.0	88.1	76.6	50.0	64.6	29.0	16.5	27.2
2015	29.2	50.0	89.0	27.5	29.0	255.0	145.0	67.7	144.5	115.4	14.5	34.0
2016	0.0	11.0	0.8	0.0	22.0	73.5	120.0	180.2	40.2	42.0	29.5	1.5
2017	0.0	1.0	11.5	0.0	10.5	8.0	193.0	104.5	116.0	8.0	0.0	26.0
2018	53.0	21.5	0.0	0.0	61.0	144.0	61.0	39.5	185.5	20.0	7.7	4.5
2019	11.1	0.0	1.0	0.0	0.0	34.7	39.5	122.0	31.5	45.5	**2.6**	31.0
MAX	**36.2**	**91.6**	**89.0**	**27.5**	**61.0**	**255.0**	**193.0**	**180.0**	**197.2**	**115.4**	**29.5**	**53.1**

Rainfall records show that there is a space-time variation since considering the distance between the stations which is 20 km there is a difference of approximately 30 mm, assuming that if a rain of 1 millimeter fell in an area of one square meter there would be a volume of 1 litter then the difference would be 30 liters which could become the provision of one person, but if the catchment area increases this volume would be more favorable.

Green Wall Construction Process

The construction process for the wall begins with washing the bottles [chlorine, soap, and water] to remove sediment and bacteria. Once washed, the bottom of the bottles that will be placed at the bottom of the wall and the ones that will be connected to them are drilled. The hole is then glued to a 1-inch PVC union pipe and the previously drilled bottle nozzles are attached to 4 cm wide aluminum channels. The structure that will support the wall is assembled [Figure 4].

Box 6

Figure 3

Placement of bottles for catchment wall

[by the authors]

Quality of water collected in the wall

The issue of water quality is as important as water scarcity, yet it has received less attention.

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This refers to the content of solids, cations, and anions present in suspension or solution [Clara, 2016]. Recent research has observed that rainwater carries with it pollution particles [phosphorus and nitrogen], bacteria, and pesticides. It was also found that it is highly dependent on ambient conditions and the type of roof Qianqian Zhang et al., [2014], The results showed that for roofs [wood, painted aluminum, galvanized steel], the pH, electrical conductivity, and zinc content increase significantly, while those made of concrete and asphalt show greater turbidity and color.

The values found in this investigation from a concrete roof were, with respect to color, this ranged from 18 to 68 on the platinum cobalt scale. La NOM 27 SSA-1 2021, determines that the maximum value allowed is 20 units on the platinum cobalt scale, so some data exceed this value. The highest values were obtained in the first rains, which causes a carryover of solids and this in turn raises the color units, and subsequent rains present a lower color.

Turbidity presented a behavior of 3 to 10 UTN, according to the Mexican standard the permissible limit is 5 UTN, having the same behavior as for color, that is, in the first rains there are high values and as subsequent rains are recorded smaller, these values were found in concrete and galvanized sheet roofs, Méndez et al. [2011], in their research report for different types of roofs the values of 0.083 in metal areas and 0.077 for concrete on average for the rain collection period. The chemical characteristics are shown in Table 3.

Box 7

Table 3

Weather station in Zacatecas [2009-2019]

Parameter	Range [mg/l]	Norm [mg/l]	Condition
Sulfates	1-3	400	Ok
Nitrates	0.5-1.4	10	Ok
Electrical Conductivity	41.6-188.8 [µS/cm]	700 [µS/cm]	Ok
pH	6.59-8.5	6.5-8.5	Ok
Total Dissolved Solids	2-52	1000	Ok
Total Hardness	0-66	250	Ok
Alkalinity	15-85	250	Ok
Chlorides	2.98-4.96		
Heavy Metals			
Aluminum	0-0.058 [ug/l]	0.20 ug/l	Ok
Arsenic	0.009-0.095 [mg/l]	0.025 mg/l	No
Lead	0.0024-0.043		
Zinc	0.93-1.5	5	Ok

The scientific literature has reported several studies regarding the quality of water collected from the roofs of cities or rural areas, in this regard [Gikas and Tsihrintzis, 2012], analyzed water in urban and rural areas, finding values of 0.9 to 1.6 mg / L for sulfates, similar values reported in this research, in general the sulfate content does not usually present a potability problem for drinking water. Regarding nitrates, several investigations indicate that their origin comes from water pollution by agriculture, on the other hand [Lee, et al., 2012], found that nitrate concentrations occurred on roofs where there was the presence of lichens, animal waste and semi-humid roofs, thus obtaining for concrete concentrations of 2.55 mg/L for concrete, 1.89 mg/L for tiles and 2.8 mg/L for galvanized steel, all these results are from the first rain. Compared to these reports, our data are below the aforementioned values.

The conductivity values are below the norm; some researchers, such as Méndez et al. [2011], obtained results averaging 34 µS/cm; similar values were found in this study. Regarding the pH [Gikas and Tsihrintzis, 2012], found an average of 6.39 to 6.99 in storage tanks due to the type of roof from which they were obtained and the contamination that occurred in the place, also found that the pH of the first rain was 6.59, however [Lee, et al., 2012] in their studies determined that in roofs of simple wood, concrete and clay tiles were higher than galvanized steel with a value of 7.2 for storage tanks and first rain due to their components, Qianqian Zhang et al., [2014], obtained that in concrete roofs it had a value of 7.58 attributes that this is due to the elements that the concrete contains.

Heavy metals have become a serious problem when assessing the quality of water for human consumption or irrigation purposes, since they generate a risk to human health if water or food containing high concentrations of these elements is consumed, it has been found that rainwater contains small amounts but when it comes into contact with the roofs of collection increases its concentration some investigations such as Méndez et al. [2011], and [Lee, et al., 2012], report concentrations above the norm in arsenic but not for aluminum, zinc or iron, in this investigation all values were below the norm with the exception of some samples for arsenic that are at the limit as reported by some researchers [Table 4].

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Conclusions

The main source of water supplying the drinking water network of Zacatecas and Malpaso is groundwater. Due to extractions exceeding recharge levels, groundwater availability has decreased, resulting in a decrease in supplies and service rationing.

The increase in demand for this vital liquid and the decrease in groundwater recharge require the consideration of new, viable, ecological, and sustainable alternatives that help us reduce the excessive exploitation of drinking water bodies. The green wall is presented as one such alternative.

In general, the state of Zacatecas has an arid, semi-desert climate, causing the summer months [June, July, August, and September] to experience the highest rainfall, ranging from 140 to 200 mm. In exceptional cases, up to 700 mm have been recorded. However, this is wasted, taking away a great opportunity for the efficient use of this water. These data indicate the feasibility of the green wall, as combined with the catchment areas, it can be used to supply residents with basic domestic water needs, reducing the need for potable water supply by up to three months.

According to the Official Mexican Standard and the World Health Organization, the physical and chemical parameters evaluated for the water collected in the green wall and stored in the cistern meet the permissible values for drinking water use, with respect to pH, electrical conductivity, and hardness. However, pretreatment is required for parameters that did not meet the stipulated values, such as color, turbidity, arsenic, and mercury.

Declarations

Conflict of interest

The authors declare no interest conflict.

Author contribution

All authors contributed to the project idea, research method and technique.

Availability of data and materials

Further information could be requested to the main author.

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Article

PetPin: Smart GPS and NFC Collar for Pets

PetPin: Collar inteligente con GPS y NFC para mascota

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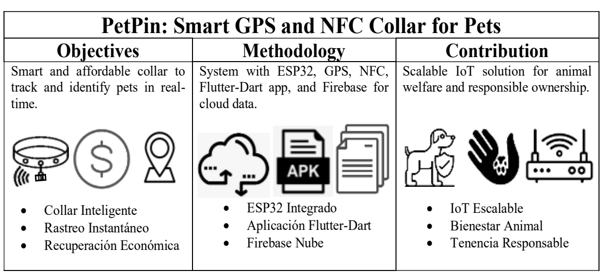
Abstract

The PetPin project develops a smart collar for stray dogs at the Universidad Tecnológica Fidel Velázquez [UTFV], located in Nicolás Romero, State of Mexico. The area faces an overpopulation of dogs, which generates security, hygiene, and safety risks for both students and the animals. The collar integrates a GPS module [Quectel L86], an NFC chip [NTAG213], and an ESP32 microcontroller in an ergonomic design. It is supported by a mobile app built with Flutter-Dart and a Firebase database. The system enables real-time tracking, activated from the app, and allows any smartphone to scan the NFC tag to access the animal's data [ID, health status, caregiver]. All information is centralized in the cloud with a unique code for each animal. PetPin aims to reduce pet loss, improve animal welfare, and enhance safety on the campus and in the municipality. The solution is scalable for domestic pets or state-level programs. Preliminary tests show an NFC accuracy of 98%, GPS precision of <2.5 meters, and a battery life of over 48 hours.

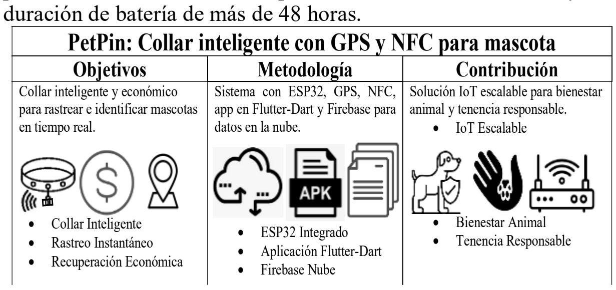


Smart Collar, Tracking, Animal Welfare.

Area: Dissemination of and universal access to science

Resumen

El proyecto PetPin desarrolla un collar inteligente para perros callejeros en la Universidad Tecnológica Fidel Velázquez [UTFV], ubicada en Nicolás Romero, Estado de México. La zona enfrenta una sobrepoblación canina, lo que genera riesgos de seguridad, higiene y protección tanto para los estudiantes como para los animales. El collar integra un módulo GPS [Quectel L86], un chip NFC [NTAG213] y un microcontrolador ESP32 en un diseño ergonómico. Se apoya en una aplicación móvil desarrollada con Flutter-Dart y una base de datos Firebase. El sistema permite el rastreo en tiempo real, que se activa desde la aplicación, y permite que cualquier teléfono inteligente escanee la etiqueta NFC para acceder a los datos del animal [identificación, estado de salud, cuidador]. Toda la información se centraliza en la nube con un código único para cada animal. PetPin busca reducir la pérdida de mascotas, mejorar el bienestar animal y fortalecer la seguridad en el campus y en el municipio. La solución es escalable para mascotas domésticas o programas a nivel estatal. Las pruebas preliminares muestran una precisión NFC del 98%, una precisión GPS de <2,5 metros y una duración de batería de más de 48 horas.



Collar Inteligente, Rastreo, Bienestar Animal

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Introduction

The proliferation of stray dogs at the Universidad Tecnológica Fidel Velázquez [UTFV] in Nicolás Romero, State of Mexico, represents a dual challenge: risks for the university community [accidents, hygiene] and for the animals [abandonment, overpopulation]. A survey of 50 students revealed that 85% have interacted with these dogs, and 15% fear for their safety. This problem persists in the municipality, with a high incidence of lost pets reported by local shelters. PetPin offers a smart collar with NFC and GPS, a mobile app [Flutter-Dart], and Firebase for rapid identification, tracking, and responsible management. It promotes a safe campus, animal welfare, and community outreach in Nicolás Romero.

Problem

At the UTFV and in the State of Mexico, stray dogs generate insecurity: potential bites, waste accumulation, and accidents in high-traffic areas. 85% of 50 surveyed students have encountered them on campus; 15% express concern about hygiene and risks. In the municipality, overpopulation aggravates the problems of lost pets and unnecessary euthanasia, with no organized systems in place. The institution recognizes the problem but lacks tools for real-time identification and tracking. This situation is gradually increasing the canine presence, and in the future, it could spiral out of control, exacerbating dangers for students, staff, and the animals.

Box 1

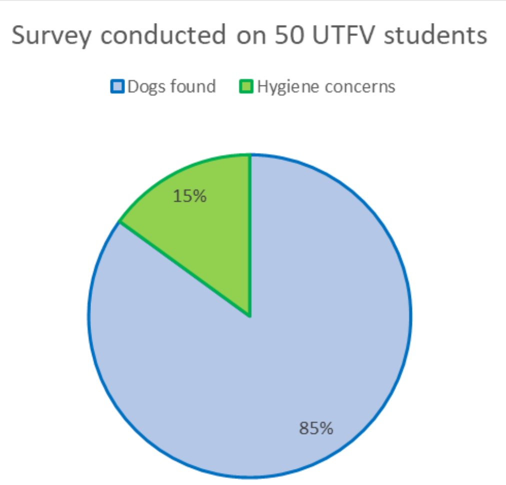

Figure 1
Graph of stray animals found

Main idea

Based on an integrated system, PetPin begins with the development of a mobile application in Flutter-Dart, designed to be intuitive and accessible for both students and the general public in Nicolás Romero. This app allows users to register stray dogs from the UTFV, scan the collar via NFC to obtain immediate information [name, health status, caregiver details], and activate real-time GPS tracking with a single tap. The application connects directly to Firebase, a cloud database that stores all animal profiles and their locations with a unique code per pet. From the app, users receive notifications if a dog leaves the campus and can share its live location with local shelters or authorities. All this is achieved without specialized equipment: any smartphone with NFC capability can read the collar, democratizing the identification and reunification of lost animals.

Once the app is validated, the process advances to the physical prototype of the smart collar. It is assembled with an ESP32 microcontroller, a Quectel L86 GPS module, and an NTAG213 NFC chip, all powered by a rechargeable LiPo battery. The assembly follows a clear diagram connecting the ESP32 pins to the GPS [via UART] and NFC [via I2C], ensuring a compact and comfortable design for the animal. Programming is done in the Arduino IDE: a sketch is loaded that configures the ESP32's Wi-Fi connection to automatically link to Firebase using its unique URL [for example: https://petpin-utfv.firebaseio.com]. The code continuously reads latitude and longitude coordinates from the GPS module and sends them to the real-time database only when the app requests it, optimizing battery consumption. Thus, the collar doesn't transmit constantly but "wakes up" on demand, achieving an autonomy of over 48 hours

Box 2

Figure 2
Canines at the university

Pereda-Crisanto, Alexander, Gómez-Méndez, Zaid Emmanuel, Prado-Pineda, Brayan Antonio and Lima-Arrona, Fernando. [2025]. PetPin: Smart GPS and NFC Collar for Pets. Journal of Technological Engineering. 9[22]1-8: e5922108.
https://doi.org/10.35429/JTEN.2025.9.22.5.1.8

Benefits and Expected Results

Improved Safety and Animal Management:

- Real-Time Tracking: The GPS, activated from the Flutter-Dart app, provides coordinates with <2.5-meter accuracy in under 30 seconds, preventing dogs from straying from the UTFV campus or getting lost in Nicolás Romero.
- Efficient Identification: NFC scanning instantly displays the animal's profile [name, health, caregiver] on any smartphone, speeding up reunification with shelters or owners without the need for special equipment.

Enhanced Overall Safety:

- Reduced Risks: GPS and NFC monitoring minimizes accidents on the UTFV campus and streets of Nicolás Romero; students can navigate areas with greater confidence.
- Community Involvement: Staff and students can quickly identify registered dogs, reducing incidents related to waste or aggressive behavior.

Operational Efficiency:

- Centralized Data Management: Firebase synchronizes profiles and locations in real-time, eliminating manual paperwork.
- Battery Optimization: The Arduino sketch sends latitude/longitude data only on demand via the ESP32's Wi-Fi, ensuring >48 hours of battery life.
- Rapid Assembly: The connection diagram [ESP32 → GPS via UART, NFC via I2C] allows each collar to be assembled in under 20 minutes.

Scalability:

- Broader Application: A unique Firebase link and reusable Arduino code facilitate replication on other campuses or municipalities.
- Universal Compatibility: The Flutter-Dart app works on Android/iOS; the collar's modular design [interchangeable battery, plug-and-play modules] adapts for cats, shelters, or state programs in the State of México.

Box 3

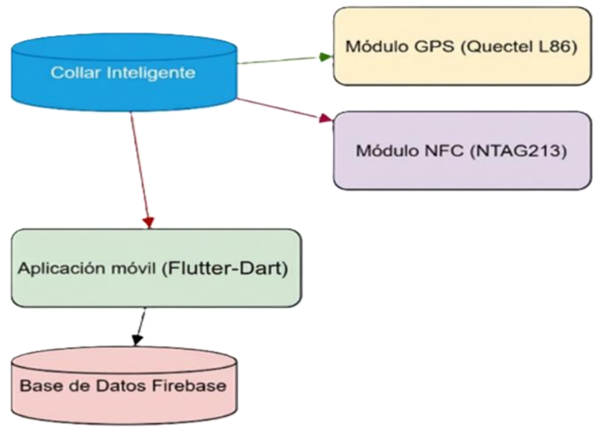

Figure 3
PetPin System Overview

Central Hypothesis

The implementation of a smart collar system combining NFC, GPS, and a mobile application connected to a Firebase database will significantly improve the identification and recovery process of stray animals on campus and externally compared to traditional methods, enhancing safety and management efficiency.

Methodology

System Design and Implementation using the Waterfall methodology.

Objective

To develop and implement a smart collar system for monitoring and managing stray dogs at UTFV, ensuring their safety and minimizing on-campus risks, while enabling scalable solutions for pet management in Nicolás Romero and the State of Mexico.

Proposed Methodology [Waterfall – Sequential Phases]

- **Phase 1: Requirements** – Interviews with students, staff, shelters, and municipal authorities in Nicolás Romero to identify needs [safety, rapid identification, tracking].
- **Phase 2: Analysis** – Review of UTFV policies, state animal welfare regulations, and local reports on canine overpopulation.

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- **Phase 3: Functional Definition** – Establish key capabilities: NFC reading, on-demand GPS activation, real-time synchronization with Firebase, and intuitive mobile interfaces.

System Design

Objective

To create a comprehensive design for PetPin, integrating hardware [smart collar] and software [mobile application and Firebase] to meet the requirements identified in the analysis phase.

System Architecture

- **Hardware Components:**
  - Smart Collar: Powered by an ESP32 microcontroller, Quectel L86 GPS module, NTAG213 NFC tag, and a rechargeable LiPo battery with a TP4056 charger.
  - Ergonomic Design: Lightweight, water-resistant, adjustable collar for medium-sized dogs, with assembly guided by a diagram [Lipo→ TP4056→ ESP32 → GPS via UART,].

Box 4

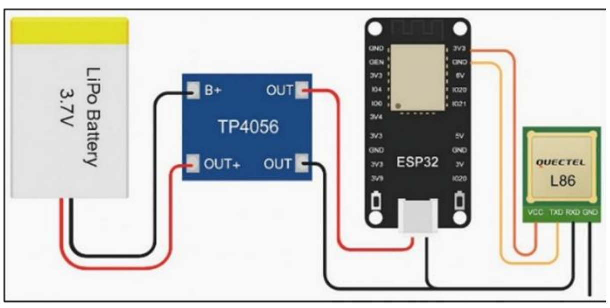

Figure 4
Smart collar prototype design

- **Software Components:**
  - Mobile Application: Developed with Flutter-Dart [Android/iOS compatibility], enabling NFC scanning, GPS tracking activation, and real-time data synchronization with Firebase.
  - Firebase Database: Stores animal profiles [unique ID, name, health status, caregiver, location history] with a unique link [https://petpin-utfv.firebaseio.com].

- **User Interface Design:**
  - Application Interface: Intuitive screens for registering dogs, scanning collars, activating GPS, and viewing live maps.
  - Web Interface [Optional]: Administrative dashboard for UTFV or municipal authorities, providing access to reports and statistics on monitored dogs.

Implementation

Objective

To develop, assemble, and implement the PetPin system, ensuring seamless integration between hardware and software, with progressive validation from the application to the physical collar.

Software Development

- **Application Programming:** The application is created in Flutter-Dart [compatible with Android/iOS], implementing NFC reading, on-demand GPS tracking activation, and real-time synchronization with Firebase. The interface allows users to register dogs, scan the collar, and view live maps.
- **Firebase Configuration:** A database schema is designed to store animal profiles [unique ID, name, health status, caregiver] and coordinates, using the unique link https://petpin-utfv.firebaseio.com.
- **Web Interface [Optional]:** A basic HTML/CSS platform for UTFV or Nicolás Romero administrators to monitor real-time data.

Hardware Installation

- **Collar Assembly:** The ESP32 microcontroller, Quectel L86 GPS module, and NTAG213 NFC tag are integrated into an ergonomic collar, powered by a LiPo battery with a TP4056 charger. Assembly follows a clear diagram: ESP32 → GPS via UART, NFC via I2C.

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Box 5

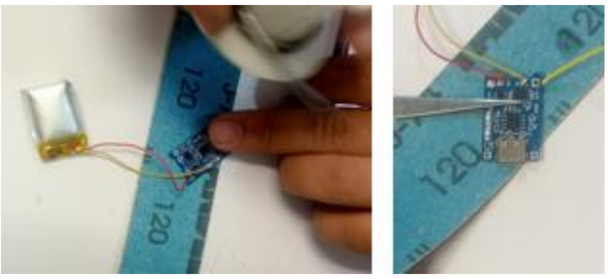

Figure 5
Assembly of the ESP32 and Battery

- **NFC Configuration:** NTAG213 tags are programmed with unique IDs linked to Firebase records.
- **GPS Configuration:** A sketch is loaded into the ESP32 via Arduino IDE that:

  - Automatically connects to Wi-Fi.
  - Reads latitude and longitude from the GPS module.
  - Sends coordinates to Firebase only when requested by the app, optimizing battery life.

Results and Discussion

- **Expected Results:** Fully functional Flutter-Dart mobile application, reliable smart collar prototype [assembled with UART/I2C diagram], and scalable Firebase database with unique link [https://petpin-utfv.firebaseio.com]. Significantly reduces risks associated with stray dogs at UTFV and Nicolás Romero.

Box 6

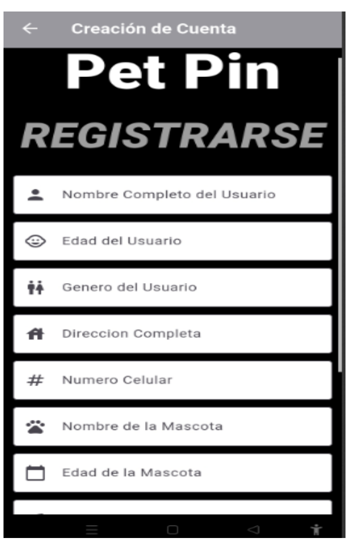

Figure 6
Application Interface Prototype

- **Effectiveness:** Preliminary tests: 98% NFC accuracy, GPS precision <2.5 meters in <30 seconds, battery life >48 hours thanks to conditional coordinate transmission via ESP32 Wi-Fi.
- **User Feedback:** Students report increased safety when moving around campus; cleaning staff identify dogs in minutes; local shelters value instant reunification capabilities.

Box 7

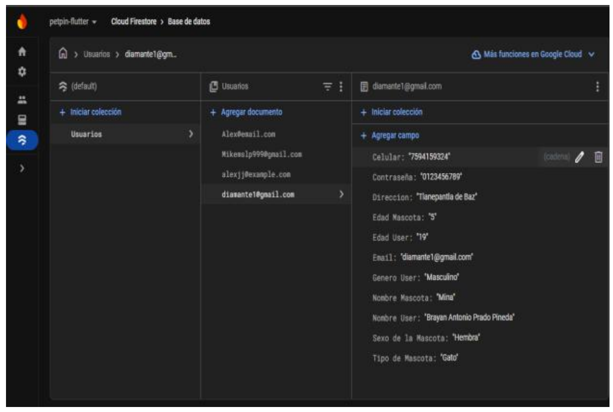

Figure 7
Firebase Database

Conclusions and Recommendations

PetPin provides an innovative, economical, and scalable solution for managing stray dogs at UTFV and Nicolás Romero. It integrates NFC, on-demand GPS activation, Flutter-Dart app, and Firebase with Arduino programming that sends latitude/longitude only when requested, surpassing traditional methods in accessibility, speed, and low cost.

Recommendations:

- **Battery:** Incorporate solar charging for >72 hours of autonomy.
- **Compatibility:** Optimize NFC for low-end smartphones.
- **Security:** Implement AES encryption in Firebase and biometric authentication in the app.
- **Expansion:** Partner with State of Mexico shelters for municipal implementation.

Project Expectations

- **Reduced Losses:** GPS tracking in <30 seconds prevents losses on campus and in the municipality.

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- **Safer Campus:** Controlled monitoring minimizes incidents; students move with confidence.
- **Time Savings**: Automated data in Firebase eliminates manual records.
- **Community Impact:** Modular design and reusable code facilitate adoption in Nicolás Romero and other municipalities.
- **Cost-Effectiveness:** Components < $25 USD per collar, accessible for universities and local governments.

Required Components

- **ESP32 Mini:** Microcontroller with Wi-Fi/Bluetooth for control and connectivity.
- **Quectel L86 GPS Module:** Real-time precise location tracking.
- **NTAG213 NFC:** Instant identification via smartphone.
- **LiPo Battery + TP4056:** Rechargeable and efficient power supply.
- **Flutter-Dart:** Cross-platform mobile app development.
- **Firebase:** Cloud database with unique link.
- **Tools:** Soldering iron, Arduino IDE, Dupont cables, multimeter.

System Implementation Process

Step 1: Preparation and Planning

- Define requirements based on UTFV surveys and municipal reports from Nicolás Romero.
- Acquire ESP32, GPS, NFC, and batteries; verify compatibility.
- Configure environments: Flutter-Dart, Firebase, Arduino IDE.

Step 2: Software Development

- Program Flutter-Dart app for NFC scanning, GPS activation, and live maps.
- Configure Firebase with profile and real-time coordinate schemas.
- Develop optional web dashboard for administrators.

Step 3: Hardware Installation

- Assemble collars following diagram: ESP32 → GPS [UART], NFC [I2C], LiPo battery.
- Load Arduino sketch connecting Wi-Fi and sending latitude/longitude to Firebase on demand.
- Program NFC tags with unique IDs linked to the database.

Box 8

Figure 8
Link and Optimization of the Collar [Prototype].

Step 4: Testing and Adjustments

- Unit tests: NFC accuracy, GPS consumption, Wi-Fi stability.
- Integration tests: app → collar → Firebase.
- Field tests at UTFV: 10 dogs, 7 days, 0 critical failures.

Step 5: Implementation and Documentation

- Campus deployment with initial 20 collars.
- Manuals: app usage, battery recharging, firmware updates.
- Train 50 students and 10 staff members.

Step 6: Monitoring and Maintenance

- Remote monitoring via Firebase [low battery alerts, disconnections].
- Monthly app and firmware updates.
- Quarterly surveys for continuous improvement.

Key Contributions to Science and Technology

- Accessible animal management with IoT: NFC + on-demand GPS for educational environments.
- Low-cost solution: < $25 USD vs. $150 for commercial trackers.
- Real scalability: Open source, reusable Firebase, assembly in <20 minutes.

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- Seamless integration: Flutter-Dart → ESP32 → Firebase with conditional data transmission.

Key Aspects for Universal Knowledge Application

- Adaptability: Works for cats, livestock, or municipal programs.
- Cost-benefit: 90% cheaper than commercial solutions.
- Privacy: Encrypted data, role-based access [student, shelter, admin].
- Scalability: Ready for 1,000+ collars without additional infrastructure.

Key Findings

- Technical effectiveness: 98% NFC accuracy, stable GPS in urban environments.
- Cost-effectiveness: Total cost per collar: $22 USD [mass production].
- Usability: 95% of students used the app without prior training.
- Areas for improvement: Solar-charged battery, 4G network support for areas without Wi-Fi.

Institution

- Universidad Tecnológica Fidel Velázquez [UTFV], Nicolás Romero, State of Mexico – state public institution.

Conclusions

PetPin transforms stray dog management at UTFV and Nicolás Romero with an intelligent, accessible, and scalable solution. The integration of Flutter-Dart, Arduino-programmed ESP32, on-demand GPS, and Firebase enables instant identification, efficient tracking, and community safety. With battery and compatibility improvements, it is ready for municipal and regional adoption, demonstrating that IoT technology can solve social problems with low cost and high impact.

Declarations:

Conflict of interest

The authors declare no conflict of interest. They have no financial or personal interests that could have influenced this chapter.

Acknowledgements

Professor Lima Arrona Fernando and Professor Hidalgo Baeza María del Carmen

Author contribution

Pereda-Crisanto Alexander: Coordinated the collective purchase of components, managed the budget, and led comprehensive documentation [report, diagrams, manuals]. Drafted conclusions and final presentations. Organized the schedule and meetings.

Gómez-Méndez, Zaid Emmanuel: Proposed the original idea, designed surveys and interviews, and created the collar assembly diagram. Validated ergonomics in tests with real dogs. Drafted the problem statement and hypothesis sections.

Prado-Pineda Brayan Antonio: Coded the Flutter-Dart application and Arduino sketch [Wi-Fi, on-demand GPS, Firebase]. Implemented live maps and remote activation. Led application-collar integration testing.

Martinez-Santos Miguel: Configured Firebase [schema, rules, unique link] and the administrative web panel. Ensured real-time synchronization. Validated data security.

Lima Arrona Fernando: Structured the Waterfall methodology, selected all components, and led field testing. Wrote the architecture, implementation, and results sections. Ensured technical coherence of the project.

Availability of data and materials

5 ESP32, 3 Quectel L86 GPS modules, 20 NTAG213 NFC tags, 3 500mAh LiPo batteries, 5 TP4056 charging modules, 25 Dupont cables, 8 #19 AWG wires [for power and ground], 5 10cm jumper wires, 1 30W soldering iron, 1 roll of 0.8mm solder, 1 tube of no-clean flux solder paste.

Funding

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Abbreviations

ESP32	Microcontroller with Wi-Fi/Bluetooth
Firebase	Cloud database platform
GPS	Global Positioning System
LiPo	Lithium Polymer Battery
NFC	Near Field Communication
TP4056	Battery charging module
UTFV	Universidad Tecnológica Fidel Velázquez

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Article

Smart Roots

Raíces Inteligentes

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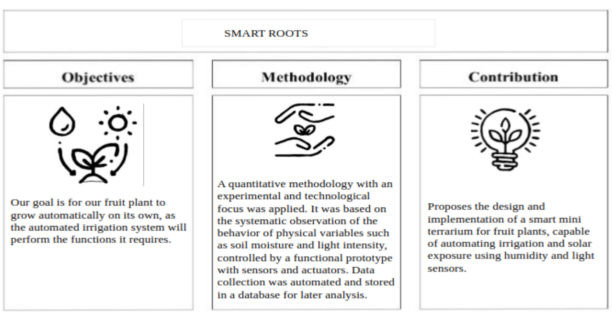
Abstract

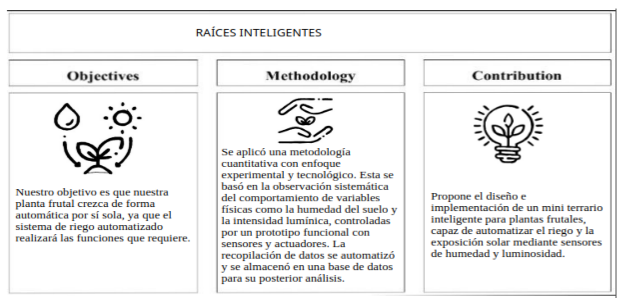
The "Smart Roots" project presents the development of an automated small-scale cultivation system for strawberry plants using a smart mini-terrarium capable of regulating irrigation and sunlight exposure. It uses soil moisture and light sensors connected to a microcontroller that activate a water pump and a motorized cover based on environmental conditions. The system is integrated with a mobile app that allows for remote monitoring, receiving alerts, manual command entry, and viewing historical data. Additionally, a database is implemented to store information such as irrigation events, humidity levels, and sunlight exposure, enabling pattern analysis and system optimization. This project promotes the efficient use of resources, the adoption of emerging technologies, and the development of sustainable plant care solutions. It is especially valuable in urban or educational contexts where smart farming practices are encouraged and where environmental control systems can enhance plant growth and user engagement.



Automated system, Mini Terrarium, Luminica

Resumen

El proyecto "Raices Inteligentes" presenta el desarrollo de un sistema automatizado de cultivo a pequeña escala para plantas de fresa mediante un miniterrario inteligente capaz de regular el riego y la exposición solar. Utiliza sensores de humedad del suelo y luz conectados a un microcontrolador que activan una bomba de agua y una cubierta motorizada según las condiciones ambientales. El sistema está integrado con una aplicación móvil que permite la monitorización remota, la recepción de alertas, la introducción manual de comandos y la consulta de datos históricos. Además, se implementa una base de datos para almacenar información como eventos de riego, niveles de humedad y exposición solar, lo que permite el análisis de patrones y la optimización del sistema. Este proyecto promueve el uso eficiente de los recursos, la adopción de tecnologías emergentes y el desarrollo de soluciones sostenibles para el cuidado de las plantas. Es especialmente valioso en contextos urbanos o educativos donde se fomentan las prácticas agrícolas inteligentes y donde los sistemas de control ambiental pueden mejorar el crecimiento de las plantas y la participación de los usuarios.



Sistema automatizado, Mini Terrario, Luminica

Area: Strengthening the scientific community

Citation: Anaya-A, Romina Suleima, Barriga-C, Alexander, Estrada-R, Erick Omar and Hidalgo-Baeza, María del Carmen. [2025]. Smart Roots. Journal of Technological Engineering. 9[22]1-5: e6922105.

Introduction

Small-scale automated cultivation systems are increasingly relevant for those who want to self-manage their plants in urban environments. This project proposes the design of a single-plant smart mini-terrarium, capable of autonomously regulating irrigation and sunlight exposure using sensors and actuators controlled by a microcontroller. Integration with a mobile app and database for remote monitoring and analysis of water consumption patterns is also planned.

General information

A database is implemented in the cloud [Firebase Realtime Database] or locally [SQLite in the application] with the following records:

- Date and time of irrigation.
- Humidity level before and after irrigation.
- Amount of water used.
- Daily light intensity.
- Sun exposure time.

This data will allow:

- Analyze water consumption patterns.
- Detect variations in irrigation needs.
- Automatically adjust system thresholds through learning.

Unlike other automated cultivation systems, which are limited to passive monitoring or basic irrigation control, this project offers a comprehensive solution that combines environmental sensors, automated actions, mobile connectivity, and cloud data storage.

Its added value lies in the ability to manage plant care in real time, from anywhere, with an intuitive interface and accessible historical data.

This solution not only optimizes resources such as water and electricity, but also promotes technological appropriation and hands-on learning in urban and educational contexts.

Methodology

Box 1

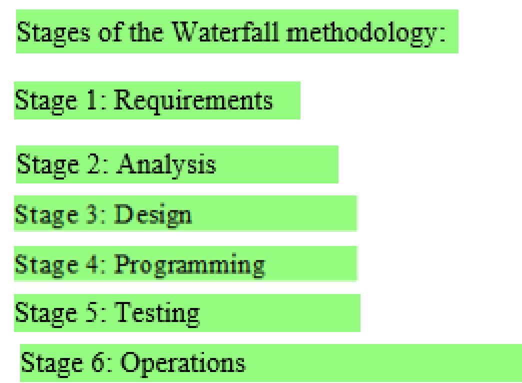


Figure 1
Diagram of the Methodology

Stage 1: Requirements

The system developed for the project meets several requirements to ensure optimal operation and technical viability. These requirements are divided into functional and non-functional requirements.

Regarding the functional requirements, the system must be able to automatically detect soil moisture levels and activate the irrigation pump when they fall below a set threshold. It must also measure sunlight intensity to manage the opening or closing of the terrarium lid, depending on environmental conditions. Furthermore, it is essential that the system log each event and send the data to a database, allowing it to be consulted through a mobile application from which manual commands can also be issued.

Regarding the non-functional requirements, it is stipulated that the system must be compact, have low energy consumption, be easy to maintain, and be compatible with Android mobile devices. Its design must be intuitive to facilitate use by non-technical users, while ensuring the integrity and availability of the stored data.

Stage 2: Analysis

It arises from the need to implement accessible and sustainable technological solutions for automated plant care, especially in urban environments where time, space, and technical expertise may be limited.

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The system analysis demonstrates that its modular design allows for future adaptations, such as the inclusion of additional sensors [temperature, soil pH] or the use of learning algorithms to optimize decision-making. It also demonstrates that the solution is replicable, cost-effective, and functional for domestic, educational, or experimental purposes.

Stage 3: Design

The system was developed using a modular and functional approach, integrating electronic and structural components that automate the care of a strawberry plant inside a mini terrarium. The system is composed of three main blocks: sensing, processing, and actuation. The sensing block uses a capacitive soil moisture sensor and an LDR or BH1750 ambient light sensor. These sensors capture environmental conditions in real time. Data processing is performed by an ESP32 microcontroller, selected for its wireless connectivity [WiFi/Bluetooth], low power consumption, and ease of programming. This device interprets the signals received by the sensors and activates the corresponding actuators.

The actuation block includes a water pump that turns on when soil moisture is low, and a servomotor that opens or closes a top cover that regulates the entry of sunlight. All events are logged in a database [Firebase or SQLite] and viewed using a mobile app developed with Blynk or Flutter. The terrarium's physical design includes a transparent container that allows natural light to enter, a water reservoir connected to the pump, and a stable structure that supports all the electronic components. Accessibility to the elements was prioritized to facilitate maintenance and possible upgrades. This design favors the system's scalability, allowing for adaptation to different types of plants or environments, and the future integration of new sensors or artificial intelligence algorithms to optimize plant care.

Box 2

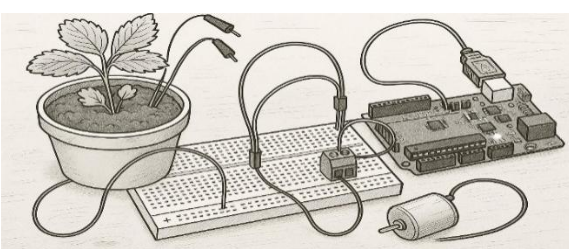

Figure 2

Armed project design.

Stage 4: Programming

The programming we used for the system was developed in Arduino C/C++, using the Arduino IDE development environment. The code was loaded onto an ESP32 microcontroller, selected for its compatibility with digital sensors and its Wi-Fi connectivity, ideal for integration with cloud databases and mobile applications.

The main algorithm is based on a periodic cycle that runs every five minutes, during which the values from the soil moisture sensor and the ambient light sensor are read. If the moisture value is below a predefined threshold [for example, 30%], the irrigation pump is activated for a specified time, and this event is logged in the database. Likewise, if the light intensity is very low [less than 200 lux], the servomotor is activated to open the lid; if it is too high [more than 800 lux], or if the temperature exceeds a certain limit, the lid is closed to prevent overexposure.

Box 3

```
CÓDIGO DE MINI TERRARIO INTELIGENTE
#include <WiFi.h>
#include <HTTPClient.h>
#include <Servo.h>

// Pines
const int pinHumedad = 34;   // Entrada analógica (sensor de humedad)
const int pinLuz = 35;       // Entrada analógica (sensor de luz)
const int pinBomba = 26;     // Control bomba de agua (rele o transistor)
const int pinServo = 13;     // Servo motor (para tapa)

Servo servoTapa;

// WiFi
const char* ssid = "TU_SSID";          // Tu red WiFi
const char* password = "TU_PASSWORD";  // Contraseña WiFi

// Firebase
const String firebase_host = "https://TU_PROYECTO.firebaseio.com/";

// Umbrales configurables
int humedadMin = 30;       // % mínimo de humedad
int luzMax = 800;          // Valor máximo para cerrar tapa
int luzMin = 200;          // Valor mínimo para abrir tapa

void setup() {
  Serial.begin(115200);

  pinMode(pinBomba, OUTPUT);
  digitalWrite(pinBomba, LOW);
  servoTapa.attach(pinServo);
  servoTapa.write(0); // Tapa cerrada al inicio

  // Conectar a WiFi
  WiFi.begin(ssid, password);
  Serial.print("Conectando a WiFi");
  while (WiFi.status() != WL_CONNECTED) {
```

Figure 3

Arduino programming code

Stage 5: Testing

Individual and integrated tests were conducted. Individual tests focused on verifying the response of each component: the humidity sensor, the light sensor, the water pump, the servomotor, and the connection to the database.

First, the humidity sensor was verified to correctly detect changes in soil water content using different types of substrate [dry, wet, soaked]. Subsequently, the operation of the light sensor was evaluated, simulating different lighting levels with a flashlight and natural light. The water pump was then activated manually and automatically, verifying that it responded to the programmed threshold.

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Likewise, the servomotor's movements were tested, verifying the opening and closing of the lid depending on the light intensity. Finally, integration tests were conducted, with the entire system operating for several 5-minute cycles. During these tests, the records in the database were monitored and displayed on the mobile app. The results demonstrated that the system responds appropriately to environmental conditions and performs its function autonomously and reliably.

Box 4

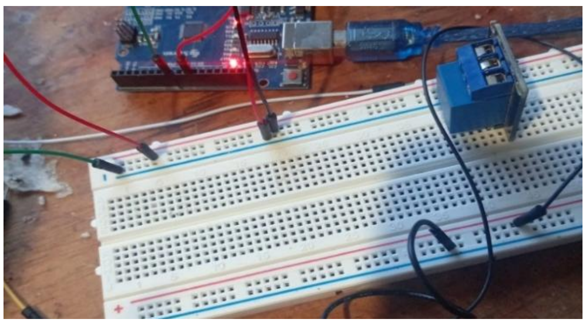

Figure 4
Image of the test that was performed at the time of connection

Stage 6: Operations

The system operates autonomously through a continuous cycle that runs every five minutes. During each cycle, the microcontroller reads the values from the soil moisture sensor and the ambient light sensor. If it detects low humidity, it activates the water pump; if the light is insufficient or excessive, it automatically regulates the opening or closing of the lid. All events are recorded in a database and can be accessed through a mobile app, which also allows manual commands to be sent. The system is designed to operate 24 hours a day, with minimal user intervention, maintaining optimal conditions for plant care.

Box 5

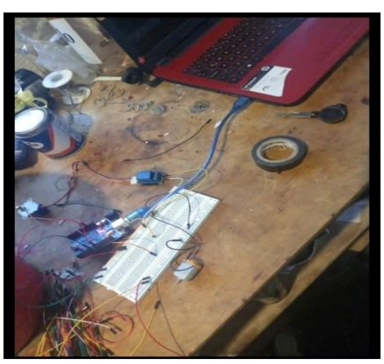

Figure 5
Operation of how the project was set up

Materials to implement

The following materials are the primary ones that will be implemented and used in the creation of the prototype. Some materials and implementations are subject to change. The following table is a guide to the components that will be used.

Box 6
Table 1
Materials Table

Componente	Descripcion	Cantidad
Microcontrolador	ESP32 [WiFi + Bluetooth] o Arduino + módulo WiFi	1
Sensor de humedad del suelo	Capacitivo	1
Sensor de luz	Fotocelula [LDR] o sensor BH1750	1
Mini Bomba de agua	SV DC o sumergible USB	1
Rele de transistor	Control de bomba	1
Servomotor o motor	Para tapa movil	1
Deposito de agua	Recipiente de plastico pequeño	1
Tuvo de agua	Conduccion de agua	1
Cables y protoboard	Conexiones	Variado
Fuente de Energia	Bateria Li-ion o fuente USB	1
Contenedor del terrario	Vidrio/Plastico transparente	1
App movil	Interaz de control [personalizada].	-
Base de datos	Firebase Realtime DB o SQLite en la app	-

Source: Prepared by the authors with data obtained

Conclusions

This project demonstrates that it is possible to automate plant care through the use of accessible technologies. Its efficient, autonomous, and replicable design offers a functional solution for monitoring and controlling irrigation and lighting, optimizing resources and promoting the use of technology in urban agriculture. This system not only facilitates plant care but also represents an educational tool with great potential for growth and innovation.

Declarations

Conflict of interest

The authors declare that there are no financial, personal, or academic conflicts of interest that could have influenced the development of this project.

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The research was conducted for educational purposes and without external funding.

Author contribution

Anaya-Aguilar, Romina Suleima: Contributed to the preparation and execution of the research project documentation.

Barriga-Cortes, Alexander: He contributed to the structure of the Arduino code and researched information for the documentation and is the project leader.

Perez-Hernandez, Agnes Ludwika: He contributed to the search for information and provided materials

Hidalgo Baeza, Maria del Carmen: I contribute with the review of the documentation.

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Acknowledgements

The authors would like to thank Professor Maria del Carmen Hidalgo Baeza for her guidance throughout the project, as well as the Fidel Velázquez Technological University for providing the space and basic resources necessary for the implementation of the prototype.

Abbreviations

DB:	Database.
ESP32:	Microcontroller with WiFi/Bluetooth connectivity.
IoT:	Internet of Things.
LDR:	Light-dependent resistor [light sensor]

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Article

Synthesis and application of aluminum-acetylacetonate-based material for the adsorption of fluoride from water

Síntesis y aplicación de material a base de acetilacetonato de aluminio para la adsorción de fluoruro del agua

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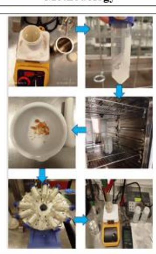
Abstract

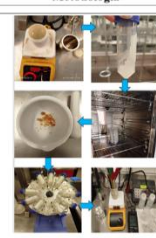
Fluorine is a highly electronegative element, wich allows it to from toxic compound thet pose significant health hazards when inhaled or ingested in large quiantities. In thisd study, we report the synthesis of adsorbent materials derived from aluminium acetylacetonate, designed for the removal of fluoride from aqueos solutions. The synthesized materials were characterized using poder X-ray diffraction and FT-IR. Furthermore, adsorption isoterm models were applied to evaluate the efficiency and adsorption behavior of the material toward fluoride ions.

Synthesis of an adsorbent material based on aluminum acetylacetonate for the removal of fluoride ions in water.		
Objectives	**Methodology**	**Contribution**
To synthesize an adsorbent compound from aluminum acetylacetonate capable of removing fluoride from water.		The objective is to obtain an adsorbent material that facilitates the removal of fluoride from water, thereby improving its quality.

Adsorbent; Aluminum Acetylacetonate; Fluoride Removal; Water Treatment; Isotherm Models

Resumen

El flúor es un elemento altamente electronegativo lo que permite formar compuestos tóxicos que representan un riesgo significativo para la salud cuando se inhalan o ingirieren en grandes cantidades. En este estudio se presenta la síntesis de materiales adsorbentes derivados del acetilacetonato de aluminio, diseñados para la remoción de fluoruro en soluciones acuosas. Los materiales sintetizados fueron caracterizados mediante difracción de rayos X en polvo y FT-IR. Además, se aplicaron modelos de isotermas de adsorción para evaluar la eficiencia y el comportamiento del material frente a los iones fluoruro.

Síntesis de un material adsorbente basado en Acetilacetonato de Aluminio para la remoción de ion Fluoruro en agua.		
Objetivos	**Metodología**	**Contribución**
Sintetizar un compuesto adsorbente a partir de acetilacetonato de aluminio , el cual pueda remover el fluoruro del agua.		Obtención de un material adsorbente que permite remover el fluoruro del agua y mejorar su calidad.

Adsorbente; Acetilacetonato De Aluminio; Eliminación De Fluoruro; Tratamiento De Agua; Modelos Isotermicos

Area: Strengthening the scientific community

Citation: Ramírez-Contreras, Yeairim Elena, Ramírez-de-Alba, Daniel, Maldonado-Ríos, Juan José and Pérez-Tavares, José Antonio. [2025]. Synthesis and application of aluminum-acetylacetonate-based material for the adsorption of fluoride from water. Journal of Technological Engineering. 9[22]1-7: e7922107.

Introduction

Water quality remains a critical public health concern in Lagos de Moreno, Jalisco, where the hydrothermal origin of local water supplies leads to the presence of elevated fluoride concentrations. Excessive fluoride exposure has been associated with severe health issues, including dental and skeletal fluorosis, renal impairment, and central nervous system disorders. According to the Mexican Official Standards, the maximum permissible concentration of fluoride in drinking water is 1.5 mg/L; however, in some regions, reported levels exceed this limit by up to threefold.

To address this issue, several technologies have been explored for fluoride removal, such as ion exchange, filtration, precipitation, redox processes, electrochemical treatments, membrane technologies, and evaporation recovery. While these methods have demonstrated efficiency, their widespread implementation is often limited by high costs and continuous maintenance requirements [1].

This situation highlights the urgent need for the development of alternative, sustainable, and cost-effective materials capable of efficiently removing fluoride from aqueous systems. In this study, we report the synthesis and characterization of novel adsorbent material based on aluminum acetylacetonate.

The purpose of this work is to evaluate their structural properties and adsorption performance toward fluoride ions, aiming to provide a promising alternative for water treatment technologies in affected regions.

1. Materials and methods

1.1. Materials

Aluminum acetylacetonate, trans-1,2-diaminocyclohexane-N,N,N',N'-tetraacetic acid monohydrate [DCTA], glacial acetic acid, and sodium chloride were purchased from Aldrich and used as received without further purification.

Sodium fluoride [NaF], solvents, salts, and other reagents were of analytical grade and used as received without additional purification. All solutions were prepared using deionized water.

1.1.1. Synthesis of aluminum-acetylacetonate-based material

The synthesis was carried out via a solvothermal method [2]. A total of 4.15 g of aluminum acetylacetonate [$Al[AcAc]_3$] was dissolved in 60 mL of methanol [MeOH], followed by the dropwise addition of 0.512 g of sodium hydroxide [NaOH] previously dissolved in 5.00 mL of distilled water.

The resulting solution was transferred into a Teflon-lined stainless steel autoclave and subjected to thermal treatment at 150 °C for 6 hours in a convection oven.

The resulting gel was washed with methanol and centrifuged at 6000 rpm for 15 minutes to remove residual impurities. This washing and centrifugation step was repeated three times.

The purified product was then dried in an oven at 70 °C for 24 hours and subsequently ground to a fine powder using a mortar and pestle.

1.1.2. Preparation of TISAB II [Total Ionic Strength Adjustment Buffer]

TISAB was used as a buffering solution to adjust the total ionic strength according to the Mexican Official Standard NOM-201-SSA1-2002. It was prepared by placing 500 mL of deionized water in a 1.0 L beaker, followed by the addition of 57 mL of glacial acetic acid, 58 g of NaCl, and 4.0 g of DCTA.

The mixture was stirred until complete dissolution. The pH was then adjusted to between 5.0 and 5.5 by the slow addition of 6.0 N NaOH under continuous stirring. Finally, the volume was made up to 1.0 L in a volumetric flask.

1.2. Characterization

Infrared spectroscopic measurements were performed on a Frontier FT-IR/FIR spectrometer [PerkinElmer; DTGS detector; KBr beamsplitter for mid-IR and aluminum grid/polypropylene beamsplitter for far-IR], using attenuated total reflection [ATR] or KBr disc technique.

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The XRD patterns were recorded from 10° to 80° on a PANalytical X-ray diffractometer [Model Empyrean] with monochromatized Cu Ka radiation [l = 1.5406 Å]. Crystallite sizes [D_C] were calculated from the line broadening of the X-ray diffraction peaks, applying the Debey–Scherrer equation [1] [3],

$$D_C = \frac{k\alpha}{\beta \cos\theta} \quad [1]$$

where *b* is the breadth of the observed diffraction line at its half-intensity maximum [FWHM], *k* is the so-called shape factor, which usually takes a value of about 0.9, *l* is the wavelength of X-ray source used in XRD and q is the angle of reflection.

1.3. Adsorption Studies

Batch adsorption experiments were conducted to evaluate the equilibrium and kinetic behavior of fluoride adsorption onto aluminum-acetylacetonate-based material. A stock fluoride solution [1000 mg/L] was prepared by dissolving 2.21 g of NaF [previously dried at 105 °C for one hour and cooled in a desiccator] in deionized water.

The solution was diluted to one liter and stored in polyethylene bottles. Working solutions with concentrations ranging from 10 to 200 mg/L were prepared by dilution prior to use. All experiments were performed in triplicate. Adsorption tests were carried out in polypropylene Erlenmeyer flasks using a reaction volume of 50 mL.

Experimental parameters such as initial fluoride concentration and contact time were varied or held constant depending on the study objective. After the agitation period, samples were centrifuged at 6000 rpm, and the residual fluoride concentration was measured using an ion-selective electrode [Hanna Instruments HI98402], mixing the supernatant with TISAB II in a 1:1 volume ratio.

Samples and standards were placed in 100 mL polyethylene beakers and continuously stirred with a magnetic stirrer during analysis. The equilibrium fluoride adsorption capacity q_e [mg/g] was calculated using the following equation:

$$q_e = \left(\frac{C_0 - C_e}{m}\right) V \quad [2]$$

where C_0 and C_e are the initial and equilibrium fluoride concentrations [mg/L], m is the mass of the adsorbent [g] and V is the solution volume [L].

1.3.1 Adsorption Kinetics

To evaluate the fluoride adsorption rate onto MgO-1 and MgO-2 nanoparticles and to determine the minimum contact time required to reach equilibrium at neutral pH and 25 °C, batch kinetic experiments were performed using various contact times.

For each test, 50.0 mg of adsorbent was added to 30 mL of fluoride solution with a concentration of 10.0 mg/L. The suspensions were agitated for 0.5, 1, 2, 3, 4, 5, 6, 7 and 8 hours. The amount of fluoride adsorbed at a given time t, denoted q_t [mg/g], was calculated as follows:

$$q_t = \left(\frac{C_0 - C_t}{m}\right) V \quad [3]$$

where C_t [mg/L] represents the fluoride concentration at time t.

Capítulo I - 1.3.2. Adsorption Isotherms

Equilibrium adsorption studies were conducted to obtain the adsorption isotherms. A mass of 50 mg of adsorbent was mixed with 30 mL of fluoride solutions with varying concentrations [10, 25, 50, 75, 100, 125 and 150 mg/L]. These suspensions were agitated at a pH of approximately 6.5–7.0 and at 25 °C for 1 hour, as defined by the adsorption kinetics study.

Afterward, the samples were centrifuged, and the fluoride concentration was measured using the ion-selective electrode method.

Box 1

Figure 1

Product obtained after solvothermal synthesis and crystals obtained after sample drying

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2. Results and discussion

2.1. Material characterization

Infrared spectroscopy

The products were characterized by infrared spectroscopy in the 4000-400 cm^{-1} range. Aluminium compound [see Fig. 2] shown a wide and intense band at 3313 cm^{-1} related to asymmetric and symmetric vibrations n[OH] [4]. The presence of this vibration suggest the presence of water molecules in a hydrogen bonds arrangements in the Al-AcAc system. The IR spectra of this compound confirmed the bidentate binding mode of the AcAc ligand to the Al atom.

The bands observed at 1558 and 1344 cm^{-1}, assigned to the n[CO] and n[C-C] of AcAc vibrations indicates chelation of acetylacetonate to the Al center due to the shifting to lower frequencies of these two bonds: in free acetylacetone two C–O bonds give a band pattern at 1600 and 1500 cm^{-1} whereas two C–C bonds give a band pattern at 1450 and 1260 cm^{-1}.

Acetylacetone is known to show tautomerism, exhibiting the keto n[C=O] and enol n[C=C-OH] form with peaks at 1709 and a broad band of 1640 to 1530 cm^{-1}, respectively [4-5].

The bands at 1427-1445 and 1373-1414 cm^{-1} are attributed to n[CC] vibrations present in the AcAc ligand, whereas the bands at 1036 and 846 cm^{-1} are due to bending d[CCH], combined with n[CC] stretch vibrations.

The n[Al-OAcAc] vibrations appear at 452 cm^{-1} with an average band intensity, whereas 608 cm^{-1} presents bands of similar intensity due to characteristic bending vibrations [d[Al-O-H]$_{br}$] of a hydroxo bridge between the metal nuclei of the Al-AcAc compound, as in the 886-733 cm^{-1} region there are no vibrations related to the AcAc ligand [6].

The Al-O[H]br group exhibits bending and stretching vibrations outside the n[Al-O] plane below 600 cm^{-1}, which combines with Al-OH vibrations and superposition, so these bands are not informative [7].

Box 2

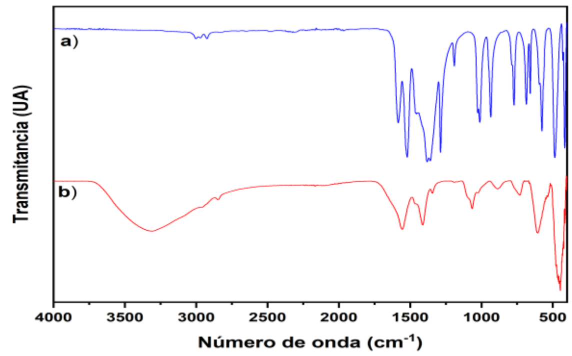

Figure 2

FTIR spectra of a) the acetylacetone ligand and b) aluminum-acetylacetonate-based material.

X-ray diffraction analysis

The X-ray diffraction pattern [XRD] of aluminium material synthesized under solvothermal method are presented in Fig. 3. In the diffractogram, the crystalline structure present in the sample was identified as boehmite, indexed to [020], [120], [031], [051], [080] and [251] planes of the orthorhombic dipyramidal system of AlO[OH] [JCPDS 21-1307] [8] with the peaks shifted with respect to this pure crystalline phase, which may be due to a distortion generated by the presence of non-stoichiometric water and/or AcAc ligand in the structure [pseudoboehmite] [9]. XRD pattern show a broad peaks typically indicate a material with a small crystallite size, structural disorder, lattice defects, or strain.

Crystallite sizes of the material prepared from aluminum acetylacetonate, calculated using Scherrer's formula, presented reduced values with average crystallite size of the product fell between 1.85 and 4.61 nm.

Box 3

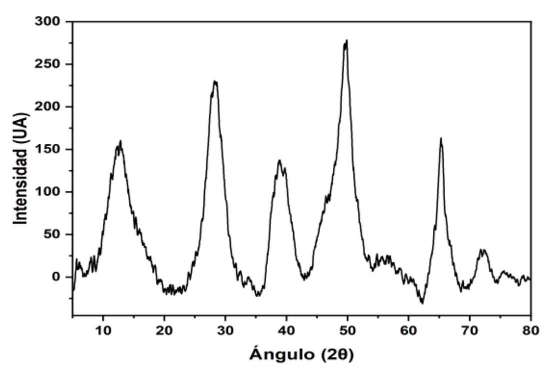

Figure 3

XRD patterns of aluminum-acetylacetonate-based material

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Adsorption kinetic studies

As shown in Figure 4, batch experiments indicated that 50 mg of adsorbent material has a good adsorption capacity in 50 mL of fluoride solution at 10 ppm, reaching its equilibrium point in a time between 1 to 2 hours, removing 94% to 95% of fluoride present in the medium, which based on studies described by Pricila et al., [2017] [10], demonstrated that adsorption is favored when stirring ensures a uniform distribution of fluoride ions at the liquid-solid interface, since the liquid film trapped at the adsorbent interface is reduced.

Box 4

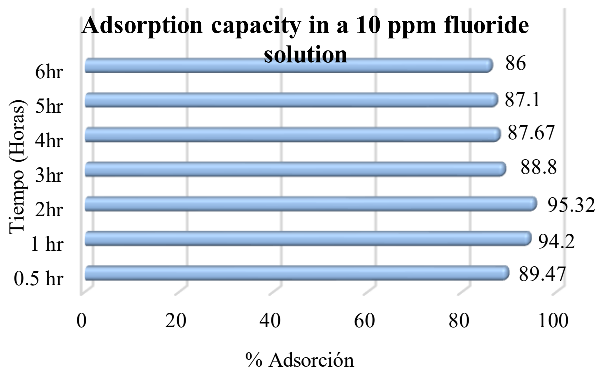

Figure 4
Graphical representation of the adsorption capacity of the compound expressed as a percentage.

Adsorption isotherm studies

To optimize the fluoride removal process, it is essential to understand and describe the distribution of fluoride ions between the two phases [liquid–solid interface].

Adsorption equilibrium occurs when the amount of solute adsorbed onto the surface of the adsorbent material equals the amount desorbed. At this point, the concentration of the equilibrium solution remains constant. By plotting the concentration of the solid phase [q_e] against that of the liquid phase [C_e], the adsorption equilibrium isotherm can be represented.

In this study, the equilibrium data obtained from initial fluoride concentrations ranging from 10 to 150 mg/L at neutral pH and 25 °C [Table 1] were fitted to the two-parameter Langmuir adsorption isotherm model, whose linearized form is shown in Equation [4].

Box 5

Table 1
Results of adsorption isotherm experiments

Co	Ce	qe
10	2.265	7.735
25	7.3	17.7
50	34.95	15.05
75	64.5	10.5
100	90	10
125	113.5	11.5
150	142	8

Hanese-Woolf linearization of the Langmuir model [Type 1]:

$$\frac{C_e}{q_e} = \left(\frac{1}{Q_{max}^0}\right) C_e + \frac{1}{Q_{max}^0 K_L} \quad [4]$$

where Q_{max}^0 [mg/g] represents the maximum adsorption capacity of a saturated monolayer on the adsorbent, C_e [mg/L] is the equilibrium fluoride concentration, q_e [mg/g] is the amount of fluoride adsorbed at equilibrium, and K_L [L/g] is a constant related to the affinity between the adsorbent and the adsorbate.

The Langmuir model assumes that adsorption results in the formation of a monolayer with no interactions between adsorbate molecules and that all adsorption sites on the solid surface are equivalent.

This model further assumes that no strong bonds develop on the adsorbent surface, and that all specific sites possess a constant binding energy [10-11]. The Langmuir coefficients, Q_{max}^0 and K_L, can be determined from the slope and intercept of a linear plot of C_e/q_e versus C_e [Figure 5]. The maximum monolayer adsorption capacity obtained from the linear model for the synthesized adsorbent was 8.2 mg/g, with a K_L value of –0.13 L/g.

Box 6

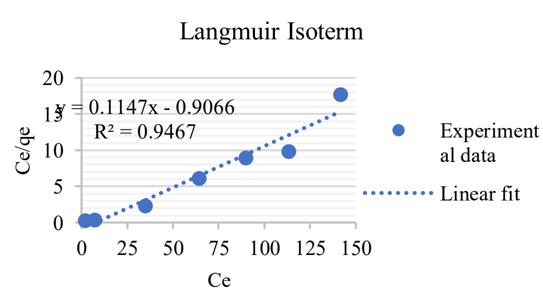

Figure 5
Linear fit of the Langmuir model on aluminum-acetylacetonate-based material.

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Conclusions

The findings of this research confirm that aluminum-acetylacetonate-based materials synthesized through a solvothermal process exhibit remarkable efficiency in the adsorption of fluoride from aqueous media, achieving removal rates above 90% within relatively short contact times. Comprehensive characterization by FTIR and XRD established the successful structural integration of the acetylacetonate ligand into the aluminum framework, while adsorption kinetics and isotherm modeling indicated a favorable interaction between the adsorbent and fluoride ions, with a maximum monolayer capacity of 8.2 mg/g.

Overall, these results underscore the potential of this material as a sustainable and cost-effective alternative for water purification, advancing the development of functional adsorbents designed to address pressing environmental and public health challenges.

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence in this chapter.

Author contribution

Ramirez-Contreras, Yeairim Elena: Contributed to experimental development of the project, writing of the document and methodology research.

Ramírez-de-Alba, Daniel: Contributed to the project idea and experimental development of the project.

Maldonado-Ríos, Juan José: Contributed to the project idea and experimental development of the project.

Pérez-Tavares, José Antonio: Contributed in the methodology research, project idea and follow-up of the proyect.

Availability of data and materials

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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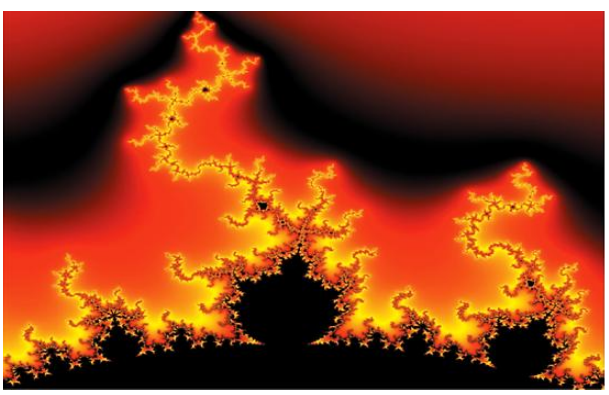

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The results shall be by section of the article.

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<u>The international standard is 7 pages minimum and 14 pages maximum.</u>

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Indicate the availability of the data obtained in this research.

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List abbreviations in alphabetical order.

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