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Journal of Engineering Applications

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Presentation of the content

In the first article we present *Application of the averages and ranges method for the evaluation of the measurement system of an automotive component manufacturing company*, by GONZÁLEZ-SÓBAL, Martín, FLORES-BÁEZ, Dulce María and SOLÍS-JIMÉNEZ, Miguel Ángel, with secondment at the Tecnológico Nacional de México, Instituto Tecnológico Superior de Huatusco, as a second article we present *Application of automation with Arduino ONE in a rustic pond aquaculture farm, to increase productivity*, by NOTARIO-PRIEGO, Ezequiel, CAMPOS-DONATO, Eugenio Josué and JIMENEZ-GIL, Antonio, with adscription in the Tecnológico Nacional de México, Campus Villahermosa, as third article we present *Benefits of the application of exoskeletons in hand rehabilitation*, by MÁRQUEZ-SILVA, Salomé, CABRERA-GONZÁLEZ, Felipe de Jesús, ALVARADO-CRUZ, Laura Benita and MANZO-REYES, José Luis, with secondment at the Universidad Tecnológica de Xicotepec de Juárez, as the fourth article we present *Evaluation of the effects of biocompost based on sugarcane cachaza on soil physical properties*, by MOJICA-MESINAS, Cuitláhuac, LORENZO-MÁRQUEZ, Habacuc, ACOSTA-PINTOR, Dulce Carolina and WONG-ARGUELLES, Cynthia, with secondment at the Tecnológico Nacional de México – Instituto Tecnológico de Ciudad Valles.

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Application of the averages and ranges method for the evaluation of the measurement system of an automotive component manufacturing company

Aplicación del método de medias y rangos para la evaluación del sistema de medición de una empresa fabricante de componentes automotrices

GONZÁLEZ-SÓBAL, Martín†*, FLORES-BÁEZ, Dulce María and SOLÍS-JIMÉNEZ, Miguel Ángel

Tecnológico Nacional de México, Instituto Tecnológico Superior de Huatusco, División Ingeniería Industrial, División Ingeniería en Gestión Empresarial.

ID 1st Author: M*artín, González-Sóbal* / **ORC ID:** 0000-0003-0038-8319, **Researcher ID Thomson:** S-7631-2018, **CVU CONAHCYT ID:** 463431

ID 1st Co-author: *Dulce María, Flores-Báez* / **ORC ID:** 0000-0001-9540-5382, **Researcher ID Thomson:** IZE-7309-2023, **CVU CONAHCYT:** 255695

ID 2nd Co-author: *Miguel Ángel, Solís-Jiménez* / **ORC ID:** 0002-8125-0989, **Researcher ID Thomson**: N-6243-2018, **CVU CONAHCYT ID**: 94216.

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Abstract

Objective: To evaluate the degree of reliability of the measurement system of a company that manufactures automotive components, guaranteeing the quality of the products supplied to its customers.

Methodology: The development of the research is based on four phases: diagnostic evaluation, definition of methods and resources, development of the R&R and analysis of results. These studies were developed based on the MSA applying the method of means and ranges.

Contribution: The results of the research determine that the current measurement system is adequate with respect to the processes analyzed, however, improvements are required to achieve the quality standards demanded by the automotive industry. Within the measurement system, 21.48% corresponds to the repeatability component, which is attributable to the measuring instrument; the reproducibility component has 5.818% and the GR&R interaction component represents 22.258%, which is within the standard recommended by the AIAG; however, this will serve as a basis for the company to orient its processes towards an improvement that allows a percentage of less than 10%.

Repeatability and reproducibility, Components of variation, Measurement system

Resumen

Objetivo: Evaluar el grado de confiabilidad del sistema de medición, de una empresa fabricante de componentes automotrices, garantizando la calidad de los productos suministrados a sus clientes.

Metodología: El desarrollo de la investigación se basa en cuatro fases: evaluación diagnóstica, definición de métodos y recursos, desarrollo del R&R y análisis de resultados. Dichos estudios fueron desarrollados basados en el MSA aplicando el método de medias y rangos.

Contribución: Los resultados de la investigación determinan que el sistema de medición actual es adecuado respecto a los procesos analizados, sin embargo, se requieren mejoras para lograr los estándares de calidad que demanda la industria automotriz. Dentro del Sistema de Medición tenemos que un 21.48% corresponde al componente de repetibilidad, la cual es atribuible al instrumento de medición, por parte del componente de reproducibilidad se tiene un 5.818% y el componente de la interacción GR&R representa un 22.258% el cual se encuentra dentro del estándar recomendado por la AIAG, sin embargo, esto servirá de base para que la empresa oriente sus procesos hacia una mejora que permita un porcentaje menor al 10%.

Repetibilidad y reproducibilidad, Componentes de variación, Sistema de medición

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* Correspondence of the Author (E-mail: mgonzalezs@huatusco.tecnm.mx)
† Researcher contributing as first author.

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Introduction

This research presents the evaluation of the measurement system implemented in a company that manufactures automotive components, through Repeatability and Reproducibility studies, with the objective of evaluating the development of metrological competences in the personnel in such a way that the company is able to demonstrate internally and externally sufficient reliability and competence in its measurement processes. The methodology developed consists of four phases: diagnostic evaluation, definition of methods and resources, development of the R&R and analysis of results.

It is important to clarify that an exhaustive quantitative study of the measurement system (personnel, instruments and methods) has not been carried out in response to the objectives of personnel development. However, an analysis is made at a level that corresponds to the objectives of this work.

The implementation of repeatability and reproducibility studies at the beginning and end of the work shows a decrease in the contribution of variation by the operators. Post-training evaluations demonstrate knowledge and ability to detect the main problems with measuring instruments (lubrication, bias, linearity, among others). These studies were developed following a methodology based on the MSA (Measurement System Analysis) with which it was possible to identify the level of reliability of the measurement system.

Problem statement

The company under study started operations in 1999 in the adhesives business, the key activity of the company is to provide high quality materials that meet the strict standards of this industry, including OEM approvals or development of new projects with alternative materials.

The production process of adhesives in its different presentations consists of a series of unitary operations, such as: master cutting of jumbo rolls, liner release, liner change, die-cutting, PULL-TAB, and die-cutting, among others. In each of these stages, from raw material to finished product, tests are carried out by the quality control department, in order to evaluate if the values obtained are within the specifications of the product in question.

In spite of the execution of these controls, there is variability of finished product in both the assembly and conversion areas, in the production of adhesives, due to the lack of specific regulations governing the production processes to ensure the quality of the final product, the quality control for these products and specifically for Manual Die-cuts, FOAMS, Planetary Rolls, BUTILOS, and Die-cuts coming from the rotary and die-cutting machine is based on the results obtained in the control of the finished product. In this sense, although there are several quality characteristics evaluated to control production, the mass of finished product is the quality reference at different points of the process.

The finished product mass evaluation process also represents an area of opportunity within the production process, since the measuring system used lacks specifications regarding the conditions in which the measuring instrument must be maintained and operated; there is also a lack of an operating and calibration procedure, as well as a verification and preventive maintenance plan.

Justification

The development of this work is supported through the application of a statistical tool known as: Repeatability and Reproducibility Studies where the criteria of the people who make decisions to accept or reject a product according to its measurement can be validated. The analysis of the measurement system (MSA), operating procedures, as well as a standardized method and operator training will be implemented. This project is intended to serve as a methodological guide for subsequent studies.

R&R study is one of the only tools that can provide the reliability to determine the degree of valid criteria that a group of people can have to make decisions, even this study can determine if the competences of the people who make decisions are depending on external factors such as: control of their hand strength, an inadequate distribution of their work center, lack of training with the measuring instrument, etc.

Literature review

Barragan (2017) in his research presents how technological progress constantly improves the techniques in devices used in new generation medicine, which requires studies to evaluate these techniques and compare them objectively with respect to previous generations. Therefore, we propose a study to evaluate the repeatability and reproducibility of retinal and choroidal thickness measurements using OCT-SS technology in a cohort of eyes with DME and to compare the variability of macular measurements obtained using spectral domain OCT versus swept source OCT in patients with DME. If we can confirm that retinal and choroidal thickness in eyes with DME can be quantified with good reliability, repeatability and reproducibility using the new OCT devices incorporating swept source technology (OCT-SS), we will be able to incorporate this novel technology into daily clinical practice.

Concluding that retinal and choroidal thickness in eyes with DME can be quantified with good reliability, repeatability and reproducibility using the new OCT devices incorporating swept source technology.

As we can see, repeatability and reproducibility studies are beginning to be used in medicine, so Perez (2019) suggests that, repeatability is applied by measurements made under conditions as stable as possible, taken with small differences in time, by the same operator and with the same equipment, reproducibility is used in measurements that are made under different conditions.

Algarín (2019) shows how in any chemical activity, involving analysis, research, manufacturing and inspection, much of the decision making and conclusions are made based on the reliable measurements that are made. The pillars of measurement are equipment, methods and personnel. Demonstrating that, within the category of equipment, mass measurements are widely used to know the error and uncertainties with which they are obtained. In addition, it adds that in many occasions organizations do not consider the impact of having quality measurement systems, the fact that measurements are not accurate can lead to errors in the calculation, analysis and conclusions of the process capability studies.

With the realization of the study, it allowed to demonstrate the conflicts referring to the people and equipment of the CAFESCA laboratory, this by means of the method of Repeatability and Reproducibility, the conflicts are referred in the case of the systematized tests to slight failures of the equipment that probably, are the location of where they are or also the attention that maintained each operator when making each one of the tests, added to that, the systematized tests with reference to the guidelines of AIAG (2002) are acceptable.

For Saravia (2020) within their analysis they conclude that organizations do not consider the impact of not having quality measurement systems, the fact that measurements are not accurate can lead to errors in the calculation, and in the analysis and conclusions of the process capability studies.

Emphasizing that when operators do not measure a part consistently, there is a risk of rejecting items that are in good condition or accepting items that are in poor condition. Adding that it is not only a matter of the operator but also if the measuring instruments are not calibrated correctly, errors can also be made and if both cases occur, we have a deficient measurement system that can make a capacity study seem unsatisfactory when in fact it is satisfactory. This can result in unnecessary costs.
In its repeatability and reproducibility study, it identifies the "part" factor as the one with the highest contribution to the total variability and that the measurement system is adequate, which is supported by recognized indices.

Garzón (2015) within the study called "Evaluation of the measurement system in the manufacture of aluminum hydroxide gel" highlights the importance of evaluating the measurement system, so that at least three components are taken into account: operator, measurement equipment and the parts or samples to the object of measurement.

Theoretical foundation

Measurement System Analysis (MSA)

The MSA Manual developed by AIAG (2002) defines measurement systems as the set of instruments or gages, standards, operations, methods, devices, software, personnel, environment and assumptions used to quantify a unit of measurement or prepare for the evaluation of a characteristic or property to be measured. It is the complete process used to obtain measurements. ISOES Consulting, (2021)

Measurement quality

"The basic concept of MSA is measurement quality, which is the statistical properties of multiple measurements obtained from a measurement system operating under stable conditions."

Bias and variance

These are the statistical properties most commonly used to characterize data quality. Bias refers to the location of the data relative to the reference (master) value. Variance refers to the dispersion of the data.

One of the most common reasons for poor data quality is excessive variation in the measurement system.

A significant proportion of this variation may be due to the interaction of the measurement system and its environment. For example, a system used to measure the volume of liquid in a tank may be sensitive to changes in ambient temperature. Then, the changes in volume detected may be due to changes in ambient temperature and changes in volume itself.

If the variation due to environmental factors is very large, it can mask the variation in the process, and in that case the data from the measurement system is not useful. One of the most important parts of the study of measurement systems is aimed at monitoring and controlling their variation.

This means, among other things, that one must learn how the measurement system interacts with its environment so that only data of acceptable quality are generated. This is very similar to the approach that is applied to understand and control the variation of a manufacturing process.

Thus, a measurement process can be viewed as a manufacturing process that produces numbers (data) as outputs. Viewing a measurement system in this way is useful because it allows us to bring in all of the concepts, philosophy and tools that have already been proven to be useful in the area of statistical process control.

During the measurement process, the variation of the process is detected, in order to have knowledge of:

- What the process should be doing.
- What may be wrong.
- What the process is doing.

Guidelines for Determining Repeatability and Reproducibility

The study of gages for variables can be performed using a number of different techniques. These are:

- Range method
- Method of averages and ranges (including the control chart method).
- ANOVA method. ISOES Consulting, (2021)

Except for the rank method, the design of the study data is very similar for each of these methods. As presented, the methods ignore variation within parts (such as rounding, flatness, etc.).

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However, the total measurement system includes not only the gage itself and its respective bias, repeatability, etc., but may also include the variation of the parts to be evaluated. The determination of how to handle the variation within the parts needs to be based on a rational understanding of the expected use of the part and the purpose of the measurements.

Finally, all techniques in this section are subject to the prerequisite of statistical stability.

Ranking and Averaging Methods

The method of averages and ranges (X & R) provides an estimate of repeatability and reproducibility for a measurement system. Unlike the method of ranges, this approach allows the variation of the measurement system to be sectioned into two separate components: repeatability and reproducibility, but not their interaction AIAG (2002).

The steps involved in performing this method according to Llamosa, Meza and Botero (2007) are:

1. Determine the equipment to be tested, the number of operators and the number of tests to be carried out by each operator.

2. Each operator carries out the corresponding tests on each piece of equipment and records the corresponding results in the respective format for subsequent study.

3. The operators repeat the measurements, but this time in a different order and without observing the measurements previously made by their colleagues.

4. With the data from the form, the range of each part of the equipment is calculated by means of the following equation:

$$R = X_{max} - X_{min} \quad (1)$$

5. The average rank of each operator is calculated using the equation:

$$\underline{R} = \frac{1}{n}\sum_{i=1}^{n} R_i \quad (2)$$

Where n: is the number of measurements made by each operator.

6. The average rank of all ranks is calculated by means of the equation:

$$\underline{R} = \frac{1}{m}\ \sum_{i=1}^{m} \underline{R}i \quad (3)$$

Where m: is the number of operators and Ri is the average rank of each operator.

7. The percentage repeatability of the measurements is calculated using the equation:

$$\%Repetibilidad\ \frac{K_1 * \underline{R}}{T} * 100\% \quad (4)$$

Where K1: is a constant that depends on the number of measurements made by each operator and gives a 99% confidence interval for these characteristics, R: is the average range of all ranges, T: is the tolerance of the measured characteristic, in this case of the tested equipment.

8. The average measurement for each operator is calculated using the equation:

$$\underline{xi}\ = \frac{1}{nr}\sum_{i=1}^{n}. Xi \quad (5)$$

Where n: is the number of tests per operator, r is the number of parts and xi is each of the operator's measurements.

9. Calculate the difference between the highest and the lowest average of the operators by means of the equation:

$$\underline{x_D} = Xmax - Xmin\ \ldots\ldots\ldots\ldots\ldots\ldots\ (6)$$

10. The reproducibility percentage is calculated by means of the equation:

$$\%\ Reprod. = \sqrt{\frac{\left(K_2 * \underline{x_D}\right)^2 - \frac{(k_1\ \underline{R})^2}{nr}}{T}} * 100\%\ \ldots\ldots\ldots\ (8)$$

Where:

K2: is a constant that depends on the number of operators and provides a 99% confidence interval for these characteristics.

xD: is the difference between the largest and smallest average of the operators.

n: is the number of tests per operator. r: is the number of parts measured.

T: is the tolerance of the measured characteristic, in this case of the tested equipment.

11. The percentage of the ratio of repeatability to reproducibility is calculated using the equation:

$$\%R\&R = \sqrt{(\%Repe)2 + (\%Repro)2} \text{ ….. (9)}$$

12. The results obtained are interpreted, using the following criteria: If %R & R < 10% the measurement system is acceptable. If 10% ≤ %R & R < 30% the measurement system may be acceptable depending on its use, application, cost of the measuring instrument, cost of repair. If %R & R > 30% the measurement system is considered as not acceptable and requires improvement in terms of operator, equipment, method, conditions, etc.

Control charts

Control charts or control charts are tools used to carry out quality control of products and were originally developed by Walter Andrew Shewhart in the 1920s; however, they were disseminated worldwide by William Edwards Deming and allow the definition of the optimum limits and parameters in a given process.

The purpose of a control chart is to observe and analyse the behaviour of a process over time, by statistically monitoring samples of the production by evaluating a quality characteristic; this is an effective procedure to ensure that a manufacturing process is under statistical control and, consequently, that the variability is due only to non-assignable causes.

Control charts for variables are used to evaluate continuous quality characteristics, i.e., those that intuitively require a measuring instrument to obtain data, such as weight, volume, voltage, length, resistance, temperature or humidity. Gutiérrez, de la Vara (2013).

Control Charts X-R-Bar

The design of control charts is a tool that determines the optimal parameters to reduce the expected cost per unit of a certain process, given a desired level of performance.

In industry, there are processes considered massive, where a large number of units, parts or components are produced during a small period of time, some of these processes perform thousands of operations per day, while others perform several tens or hundreds, in both cases we are facing a massive process; if in addition, the output variable of interest is of continuous type, which requires a measuring instrument to obtain data, we are in the ideal conditions to apply the X-R control charts. Gutiérrez, de la Vara (2013).

Average X control charts are tools belonging to statistical process control, to improve the quality and productivity of a company; they allow monitoring changes or shifts in the mean in a process by establishing three parameters: the sample size (n), the sampling interval (h) and the control limit coefficient (k).

The X-R control charts are diagrams for the study of continuous variables applied to massive processes, where subgroups are obtained periodically, measured and the mean and range are calculated and recorded in the corresponding chart; at the exit of the process, every certain time or number of pieces, a sample or subgroup is taken, to which the corresponding quality characteristic is determined and the mean and range are calculated for each period of time; the X chart allows the variation between the subgroups to be analysed to detect changes in the process mean, while the R chart analyses the amplitude or magnitude of the variation of the process.

R&R study by ANOVA method

The r&R studies make it possible to evaluate experimentally that part of the total variability (σ^2total) observed in a process through the measurements made is attributed to the measurement system; in this sense, the sources of variability that can be evaluated through the r&R study are: variability attributed to the product itself (σ^2prod), variability due to the measuring instrument (σ^2instr) and the variability introduced by the operators (σ^2oper); therefore, the total variability observed is given by the following equation, where the total variability is the sum of the above-mentioned factors.

$$\sigma^2 total = \sigma^2 prod + \sigma^2 instr + \sigma^2 oper \quad (10)$$

In this sense, as can be seen in equation 11, repeatability corresponds to the variability given by the measuring instrument or non-human factor, and equation 12 shows how reproducibility is given by the variability introduced by the operator or human factor.

$$\sigma^2 repeti = \sigma^2 instr \quad (11)$$

$$\sigma^2 reprod = \sigma^2 oper \quad (12)$$

Therefore, the total variability obtained through an r&R study (σ^2r&R) corresponds to the sum of repeatability and reproducibility as shown in the equation below:

$$\sigma^2 r\&R = \sigma^2 repeti + \sigma^2 reprod \quad (13)$$

For the determination of the repeatability and reproducibility of a measurement system, three methods can be used, which are based on the statistical evaluation of the dispersions of the results, either in the form of range or through the variance or standard deviation; these methods are range, mean and range and analysis of variance. AIAG (2002).

Methodology

The following diagram represents the methodological structure for the development of the R&R study:

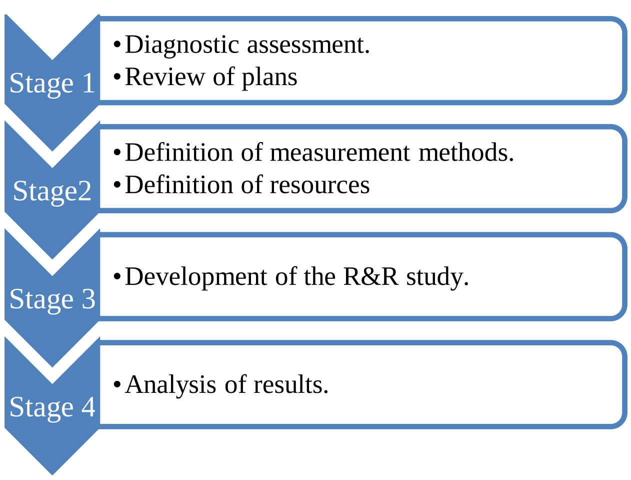


Figure 1 Methodology of analysis
Source: Own elaboration

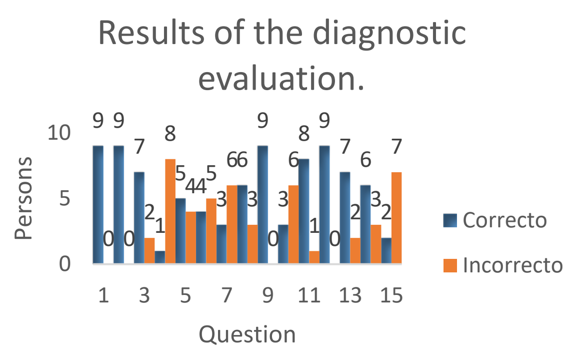
Stage 1

Diagnostic assessment of operators

Training is given to the personnel involved in the inspection process, a total of 6 operators and 3 inspectors, with emphasis on the following points:

- Components of a calibrator.
- Handling of the caliper.
- Parts that can be measured with the caliper.

The above points were identified on the basis of a diagnostic assessment, the following graph shows the results of this instrument:



Graphic 1 Diagnostic assessment results.
Source: Own elaboration

Review of plans

This process was used to determine the dimensional characteristics of the part numbers to be evaluated and to identify the measurement tolerances, it is worth mentioning that, due to company confidentiality, it is not possible to present these drawings, so we only present the tables indicating the tolerances of the three products evaluated in the study.

We limit ourselves to presenting the tables indicating the tolerances of the three products evaluated in the study, which, for practical purposes, we will call them A, B and C.

Cota	Tolerance
A	15mm +/- 1mm
B	50mm +/- 1mm
C	35mm +/- 1mm

Table 1 Dimensions of dimensional drawing component A
Source: Own elaboration

Cota	Tolerance
A	10mm +/- 0.5mm
B	434mm +/- 2mm
C	40mm +/- 2mm

Table 2 Dimensions of dimensional drawing component A
Source: Own elaboration

Cota	Tolerance
A	5mm +/- 0.5mm
B	166mm +/- 2mm
C	40mm +/- 2mm

Table 3 Dimensions of the dimensioned drawing component C
Source: Own elaboration.

Step 2.

Definition of measurement methods.

For the development of the study, the parts to be evaluated were randomly provided by the maquila area, including two parts above the upper specification and two parts below the lower specification, this applies to the three products to be evaluated. It is worth mentioning that the study is made up of 10 parts, three operators and each operator performs three repetitions.

Definition of resources

The following measurement instruments were defined as part of the study:

- Nine calipers model 500-196-30, resolution: 0.005, unit of measurement: inches.

- Three calipers model 500-196-30 with resolution: 0.0005, unit of measurement: inches.

- Data collection forms, identifying the measuring instrument, part number, characteristic to be measured, number of pieces, name of operators and number of repetitions.

Stage 3

Development of the R&R Study

The study was carried out in the following phases:

1. Preparation of the pieces. The sample pieces to be evaluated are prepared, maintaining their confidentiality during the study. The following image represents the part to be evaluated of product A.

Figure 2. Part number A
Source: Own elaboration

2. Inform area leaders. Area leaders are notified about the execution of the study, as well as about the participating operators and inspectors, in order to organise and manage the study in the best possible way.

3. Form teams of operators: These are defined by the leaders of the maquila and conversion area, bearing in mind that each participant belongs to the same process and that they have the necessary training for the proper handling of the measuring instrument.

4. Verification of the measuring instrument: This point is of vital importance as it must be verified that the measuring instrument to be used is calibrated, and that its date is valid, for this purpose the identification label must be checked.

5. Data collection. For this point, each operator performs the measurements in random sequence according to the following table, for reasons of confidentiality only the order of collection for part A is presented:

Measurement sequence Part A										
1st attempt	6	9	1	2	5	10	4	3	7	8
2nd attempt	4	3	9	6	10	8	5	1	2	7
3rd attempt	3	2	6	8	4	10	7	5	9	1

Table 4 Measurement sequence of component A
Source: Own elaboration.

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1. Once the data collection has been completed, the data are sorted according to the following template, only the data from part A are presented:

ESTUDIO R&R POR VARIABLES REPETIBILIDAD Y REPRODUCIBILIDAD DE DISPOSITIVOS TOMA DE DATOS									
No. de parte y descripción:					No. del dispositivo				
Parte A					CAL010				
Característica:					Dispositivo de medición:				
-Cut convertido de forma manual (anc					Vernier Digital				
Intentos	Operadores		Piezas				Fecha de estudio		
r = 3	j = 3		n = 10				15/12/2022		
Operador	A			B			C		
Pieza	1	2	3	1	2	3	1	2	3
1	9.87	9.3	9.73	9.76	9.76	9.92	9.81	9.7	9.74
2	10.02	9.21	9.92	9.7	10.1	9.82	9.78	9.76	9.97
3	9.65	9.88	9.67	10.1	9.8	9.81	9.64	9.76	9.68
4	9.6	9.88	9.8	9.82	10.1	9.85	9.84	9.82	9.87
5	9.67	9.66	10	9.84	9.76	9.85	9.82	9.83	9.73
6	10.3	9.72	9.89	9.8	9.76	10.52	9.86	9.88	9.85
7	9.92	9.42	9.99	10.1	10.1	9.72	9.94	9.66	9.6
8	9.77	9.9	9.93	9.9	9.88	10.52	9.9	9.78	9.69
9	9.89	9.75	9.81	10.2	9.68	10.18	9.77	9.72	9.78
10	9.73	9.53	10.1	9.95	9.98	10.17	9.78	9.69	9.71

Table 5 Component A data collection.
Source: Own elaboration.

It is worth mentioning that, due to company confidentiality, only the data collected for component A is presented, and in the same sense the results obtained from the study will be presented.

Results

Analysis of results

With the results obtained from the measurement system, it was determined that it is adequate with respect to the processes that are carried out in the different work areas, such as the conditioning and inspection of the finished product. But it must be improved if we want a system of excellence as demanded by the automotive industry worldwide; this is nothing more than the updating of measuring equipment such as gauges that have a pressure valve.

In this study we have a 21.484% of Repeatability (EV) which indicates that the variability that exists in the measurement system is caused by the device, the variation that exists on the part of the operators in the measurement system is 5. 818% of Reproducibility (AV); as part of the estimated combined variation of Repeatability and Reproducibility (GRR) we have 22.258% which is within the range of acceptance of the measurement system (between 10% and 30%) established by the AIAG, so it is acceptable but work must be done to achieve a percentage of less than 10%.

However, it is concluded that when working with this type of materials (adhesive and soft) and in order to have the most reliable measurement possible, it depends not only on the measuring equipment but also on a good training and recruitment programme, which is explained in the recommendations.

As far as the quality department is concerned, there are no problems with non-conforming products, as they are within their permissible limits, but there is always room for improvement and these improvements would have a positive impact on the organisation.

Funding

This research did not obtain funding from any public or private institution.

Conclusions

This research developed an analysis for active gauges within the measurement system in an automotive components manufacturing company, through direct observations of the production process and information provided by production operators, as well as through data collection and analysis. It was possible to identify the performance level of the measurement system, which, according to the results shown in the previous section, is evaluated as acceptable with areas for improvement, which validates the hypothesis of this research, since the company guarantees the level of reliability of its products for its customers.

Therefore, the factors influencing the variability of the process show that the behaviour of the production depended on the conditions of the measuring instrument, as well as the operators on shift and the methods used by each one of them, since the personnel with less time in the company presented a greater deficiency in their measurements.

With the analysis of the Repeatability and Reproducibility studies, failures were identified in the measurement system, which placed 7% of the studies at an unacceptable level and 80% of the studies at an acceptable level with reservations, i.e. subject to improvement, and 13% with a degree of excellence.

The measuring instrument is not suitable because, in the company, it is used for soft material measurements and there are personnel who use a lot of force when taking measurements or, on the contrary, less force, which was reflected in the repeatability component, since the personnel were not constant in their measurements.

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Application of automation with Arduino ONE in a rustic pond aquaculture farm, to increase productivity

Aplicación de la automatización con Arduino UNO en una granja acuícola de estanque rustico, para incrementar la productividad

NOTARIO-PRIEGO, Ezequiel†*, CAMPOS-DONATO, Eugenio Josué and JIMENEZ-GIL, Antonio

Tecnológico Nacional de México, Campus Villahermosa.

ID 1st Author: *Ezequiel, Notario-Priego* / **ORC ID:** 0000-0002-3791-1823, **Researcher ID Thomson** G-2613-2018, **CVU CONAHCYT ID:** 407736

ID 1st Co-author: *Eugenio Josué, Campos-Donato* / **ORC ID:** 0009-0005-2884-4656, **Researcher ID Thomson** JLM-4400-2023, **CVU CONAHCYT ID:** 537154

ID 2nd Co-author: *Antonio, Jimenez-Gil* / **ORC ID:** 0009-0002-5629-6771, **Researcher ID Thomson:** JLM-4482-2023, **CVU CONAHCYT ID:** 175806

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Abstract

This project has the goal of monitoring the Mechatronic Design process carried out for the implementation of an automated monitoring and control system of the necessary physical-chemical conditions that must be considered in a rustic pond dedicated to the production and breeding of tilapia; with the purpose of optimizing fish production in Jalpa de Méndez, Tabasco. Through a mechatronic system based on ARDUINO UNO consisting of: control, actuation and sensing system that achieves intelligent decisions to problems in branches of the rural aquaculture sector that do not have equipment for the development of automated products.

Control Arduino, Aquaculture

Resumen

Este proyecto tiene como meta el seguimiento al proceso de Diseño Mecatrónico realizado para la implementación de un sistema automatizado de monitoreo y control de las condiciones físico-químicas necesarias que se deben de considerar en un estanque rustico dedicado a la producción y cría de tilapia; con el propósito de optimizar la producción piscícola en Jalpa de Méndez, Tabasco. A través de un sistema mecatrónico basado en ARDUINO UNO constituido por: sistema de control, actuadores y sensores que logre decisiones inteligentes a problemas en ramas del sector rural acuícola que no dispone de equipos para el desarrollo de productos automatizados

Control, Arduino, Acuacultura

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* Correspondence of the Author (E-mail: ezequiel.notariop@villahermosa.tecnm.mx)
† Researcher contributing as first author.

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Introduction

Aquaculture plays a crucial role in global food security, and tilapia farming has gained prominence due to its high growth rate and adaptability. This article explores the automation of tilapia farms in rustic ponds as an innovative strategy to improve efficiency and sustainability in tilapia production. It discusses the technologies involved, the benefits obtained and the implications for the future of sustainable aquaculture.

Fisheries and the development of the fish farming sector is currently one of the fastest growing industries in recent decades around the world, with per capita consumption of combined fish products at levels of 15.8 kilos per year.

In recent years, however, it is also one of the most threatened sectors, not only because overfishing is exceeding the limits of sustainability, i.e. it is taking place at a faster rate than replenishment, but also because several fish species are being depleted. The above situation, added to the alarming realities of human overpopulation, soil desertification, freshwater scarcity and environmental pollution, are the consequences of accelerated environmental degradation worldwide, and therefore man is obliged to come up with solutions for the protection of ecosystems.

Tilapia farming in rustic ponds has been a common practice in regions with limited resources. However, environmental challenges and the need to increase efficiency have led to the development of automation systems. This article examines how automation improves farming conditions and optimises available resources in rustic ponds.

Tilapia is a freshwater fish species that has become one of the most popular for aquaculture. Its fast growth, disease resistance and low production cost make it an attractive option for small-scale farmers.

Arduino UNO automation of a tilapia farm can help improve efficiency and productivity. Automated systems can monitor and control water parameters, feed the fish and perform maintenance tasks regularly and efficiently.

In a rustic pond, automation can be a challenge. Rustic ponds are often smaller in size and have less infrastructure than commercial ponds. However, there are some solutions that can help automate a tilapia farm in a rustic pond.

Methodology to be developed

Figure no. 1 shows the methodology used, starting with the characterisation of the study area, where a reconnaissance of the work areas will be carried out to identify the conditions in which the current state of the aquaculture farms is, to determine the operation and functioning of the same, to obtain a diagnosis, after the characterisation, we will continue with the consultation of different information providers, to identify the current technologies for the monitoring and control of the physicochemical elements that should be considered in the farm, making a comparative table where the characteristics, advantages and disadvantages and costs of each one of them are observed,

Then, an analysis of the control logic, system architecture design, system development and implementation of the system for interaction with the different parameters to be monitored will be carried out, and finally, the system functionality tests will be carried out, the results obtained will be evaluated and suggestions for improvement will be made.

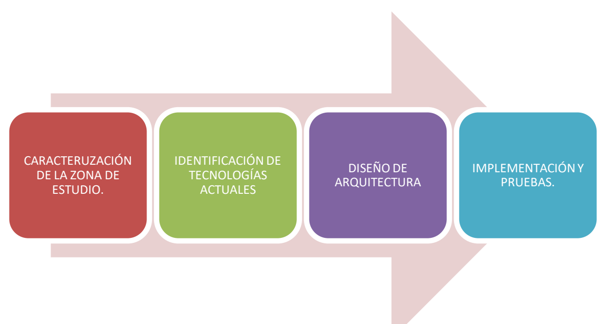

Figure 1 Diagram representing the methodology applied
Source: Own elaboration

Development

In order to carry out this project, several aspects are evaluated, such as the following:

Water quality control systems

Water quality monitoring systems are essential to keep fish healthy. These systems can monitor oxygen levels, pH, temperature and other water parameters.

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Water quality monitoring systems are available that are relatively affordable and easy to install. These systems can use sensors to collect data and send it to a controller. The controller can use this data to trigger devices that adjust water quality.

Automatic feeding systems

Automatic feeding systems can help ensure that fish receive the right amount of feed in a timely manner. These systems can use sensors to detect the presence of fish and dispense feed automatically.

There are automatic feeding systems that are suitable for small ponds. These systems typically use a timer to dispense feed at regular intervals.

Maintenance systems

Maintenance systems can help to carry out regular maintenance tasks. These systems can be used to clean ponds, change water and perform other work.

There are maintenance systems that are suitable for small ponds. These systems often use motors and pumps to perform maintenance tasks.

Benefits of automation

Automation of a tilapia farm can offer a number of benefits, including:
Improved efficiency

Automated systems can help reduce the time and effort required to manage a tilapia farm.

Increased productivity

Automated systems can help improve fish growth and survival.

Reduced costs: Automated systems can help reduce production costs.

Automation Technologies:

Water Quality Monitoring.

Advanced sensors constantly monitor parameters such as temperature, pH and dissolved oxygen levels. Automated systems adjust these parameters to maintain an optimal environment for tilapia growth as shown in the table below

Parameter	Optimum range
Oxygen	>4.0mg/L
PH	6.0mg/l – 9.0mg/l
Temperature	27º C - 30º C
Nitrite	< 0.25 ppm

Table 1 Parameters to be monitored
Source: Own elaboration

Automated Feeding

Automated feeding systems dispense feed at specific times and in precise amounts, minimising wastage and optimising feed conversion rate.

Health Monitoring

Underwater cameras and health sensors monitor the behaviour and physical condition of the fish. Early detection of diseases enables fast and effective interventions.

Benefits and challenges

Benefits

- Increased production efficiency.
- Reduced use of resources such as feed and water.
- Improved fish health and growth.
- Reduced long-term operating costs.

Challenges

- Initial cost of implementation.
- Technical maintenance and staff training.
- Adaptation to specific farm conditions.

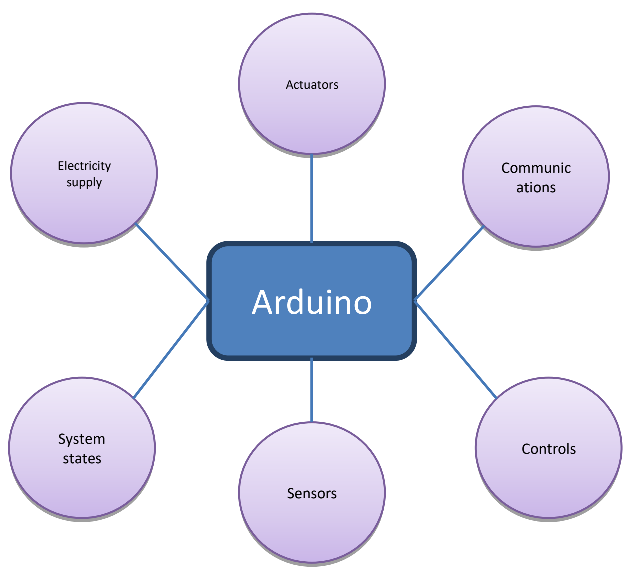

Figure 2 Structure of the system
Source: Own elaboration

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Results

Technology transfer was achieved with the implementation of this project.

Technical assistance is provided for the implementation of the system.

The system will undoubtedly lead to a reduction of maintenance and maintenance costs of the ponds.

The optimisation of resources leads to savings in basic raw materials, time and effort.

Therefore, this system will increase tilapia production significantly.

Acknowledgement

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Conclusions

The automation of tilapia farms in rustic ponds represents a significant advance in sustainable aquaculture. Despite the challenges, the long-term benefits in terms of efficiency and sustainability are evident. Continued research in automation technologies, together with appropriate training for farmers, will continue to drive the development of this technique.

Collaboration between scientists, engineers and farmers is essential to maximise the potential of automation in aquaculture and to ensure a stable and sustainable supply of tilapia for future generations.

Tilapia production is significantly increased by applying an automated system, as the time, resources and labour required are optimised, resulting in lower losses, wastage and specimen mortality.

An important improvement for this system would be the use of renewable energy such as solar energy, in order to have a sustainable system that is friendly to the ecosystem.

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Benefits of the application of exoskeletons in hand rehabilitation

Beneficios de la aplicación de exoesqueletos en la rehabilitación de la mano

MÁRQUEZ-SILVA, Salomé†*, CABRERA-GONZÁLEZ, Felipe de Jesús, ALVARADO-CRUZ, Laura Benita and MANZO-REYES, José Luis

Universidad Tecnológica de Xicotepec de Juárez. Av. Universidad Tecnológica No. 1000, Tierra Negra, 73080 Xicotepec de Juárez, Pue.

ID 1st Author: *Salomé, Márquez-Silva* / **ORC ID:** 0000-0003-4901-9290

ID 1st Co-author: *Felipe de Jesús, Cabrera-González* / **ORC ID:** 0009-0007-2872-0316

ID 2nd Co-author: *Laura Benita, Alvarado-Cruz* / **ORC ID:** 0000-0001-5565-1001

ID 3rd Co-author: *José Luis, Manzo-Reyes* / **ORC ID:** 0009-0001-4957-3083

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Abstract

The hand is a complex anatomical and biomechanical functional component, indispensable for performing Activities of Daily Living and which has two primary functions: grasping and touching. Injuries in this anatomical region constitute between 6.6% and 28.6% of the injuries of the musculoskeletal system, being young male patients between 21 and 30 years of age the most affected and the most predominant injuries were fractures, contusions and sprains. Exoskeletons are mechanical and electrical devices with very specific applications in the field of rehabilitation; they contribute to the substitution or potentiation of basic functions of a body segment, thus, exoskeletons become useful to facilitate simple motor activities. The present study sought to determine the benefits of the application of exoskeletons for hand rehabilitation through a literature review of various databases. It was possible to identify that more than half of the articles included in the research describe a benefit in the rehabilitation processes, although there is a lack of quantitative data and anatomical foundations, it is determined a positive factor to include exoskeletons in the rehabilitation practice.

Exoskeletons, Rehabilitation, Hand, Disability

Resumen

La mano es un componente anatómico y biomecánico complejo funcional, indispensable para realizar las Actividades de la Vida Diaria y la cual tiene dos funciones primordiales: la prensión y el tacto. Las lesiones en esta región anatómica constituyen entre el 6,6 y el 28,6% de las lesiones del sistema musculoesquelético, siendo los pacientes hombres jóvenes entre 21 y 30 años de edad los más afectados y las lesiones más predominantes fueron fracturas, contusiones y esguinces. Los exoesqueletos son dispositivos mecánicos y eléctricos con aplicaciones muy específicas en la rama de la rehabilitación, coadyuvan a la sustitución o potencialización de funciones básicas de un segmento corporal, de este modo, los exoesqueletos llegan a ser útiles para facilitar actividades motoras simples. El presente trabajo buscó determinar los beneficios de la aplicación de los exoesqueletos para la rehabilitación de mano mediante una revisión bibliográfica de diversas bases de datos. Se logró identificar que más de la mitad de los artículos incluidos en la investigación, describen existir un beneficio en los procesos de rehabilitación, aunque se carece de datos cuantitativos, y fundamentos anatómicos, se determina un factor positivo incluir a los exoesqueletos en la práctica rehabilitadora.

Exoesqueletos, Rehabilitación, Mano, Discapacidad

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* Correspondence of the Author (E-mail: salome.marquez@utxicotepec.edu.mx)
† Researcher contributing as first author.

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Introduction

The hand is a complex anatomical and biomechanical functional component, indispensable for performing Activities of Daily Living (ADL) and which has two primary functions: grasping and touching. The biomechanical characterization of the grip involves the determination of the different kinematic and dynamic variables that affect its different phases: transport, grip formation and manipulation, as well as their relationship with the anthropometric characteristics of the subject and the object (Vázquez, Díaz, Lázaro, & Guamán, 2021). On the other hand, injuries in this anatomical region constitute between 6.6 and 28.6% of injuries to the musculoskeletal system, with young male patients between 21 and 30 years of age being the most affected (Arroyo & Quinzaños, 2022). Students and housewives account for almost half of the population treated for hand and wrist injuries (Arroyo & Quinzaños, 2022). The most predominant injuries were fractures, contusions, and sprains. In addition to requiring timely specialized treatment to avoid complications and permanent disability (Arroyo & Quinzaños, 2022). The success of hand rehabilitation after impairments depends on timing, intensity, repetition, and frequency, as well as task-specific training. Considering the continuing limitations imposed on therapist-led rehabilitation and the need for better outcomes, robot-assisted rehabilitation has been explored (Haghshenas-Jaryani, Patterson, Bugnariu & Wijesundara, 2020).

Anatomically the hand is part of the upper limb; composed of twenty-seven bones divided into three groups: the carpus made up of 8 bones, the metacarpus of 5 bones and 14 phalanges (Ferrin, et al., 2021) as well as the musculature, tendons, ligaments, nerves and blood vessels (Rodriguez et al., 2020) in carpometacarpal, metacarpophalangeal and interphalangeal joints. Based on the normal anatomy of the hand, the development of technologies has been sought for the efficient development of the mechanical processes of the segment, which contribute to the reduction of injuries and rehabilitation, through devices such as exoskeletons, understood as rigid external structures that incorporate actuators that allow controlled and precise movements as well as sensors that provide movement information related to angle, speed and acceleration (Broche & Torres, 2020).

Can also be defined as devices that dress the human being or a part of his body, with very specific purposes and applications, such as support or enhancement of functionality in subjects that require it. In a very general way it can be said that an exoskeleton is a frame that allows or facilitates the movement of its wearer, it can be made of different materials and are divided into electrical or active and mechanical or passive (Zubizarreta, 2021), the electrical ones have as main function to enhance the strength while the mechanical ones help mainly to redistribute the weight. Among the most common uses of exoskeletons, we can find several activities, such as physical training, military use, transport of heavy materials, rescue, functionality in patients with disabilities and rehabilitation. In the most advanced ones, they make it possible to capture the patient's muscular electrical activity (electromyographic signals) or electroencephalography (EEG), related to the intentionality of the movement (Broche & Torres, 2020). The use of an exoskeleton provides very specific advantages to its user such as: reduced exhaustion, reduced risk of injury, increased functionality and increased work productivity. Rehabilitation medicine is one of the fields with the greatest development in the use of exoskeletons, with the aim of helping in the recovery of lost functionality when possible, otherwise, it seeks to replace it (Zubizarreta, 2021). The designs of hand exoskeletons vary in weight, complexity and total cost, with a unidirectional and bidirectional mechanism, the first is based on the opening or closing of the hand, with active rehabilitation through pneumatic or electrical mechanisms where the patient performs voluntary movements during each activity and the second are passive actuators based on automatic motion control where the therapy is guided in its entirety by the device. Also standing out is the production of mixed exoskeletons that offer greater benefit in rehabilitation (Arias, 2021). In an attempt to provide the user with the full range of motion of the human hand, most of these devices have become bulky and complex and, because of this, are restricted to a single functional activity: opening the hand or pinching (Triolo & BuSha, 2022).

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Theoretical frame

Most of the articles reviewed refer to obtain a positive result for intervention processes and functionality, it is described as in the case of Arias (2021), that the users participating in the study presented some type of injury or it is difficult for them to place the exoskeleton. This suggests that more specific parameters should be established for the anthropometric measurement of the hand structures, in order to increase the benefit of exoskeletons in the rehabilitation area. In addition, it is found in the literature that exoskeletons have direct action in the decrease of local effort, decrease of biomechanical load, increase of cardiac and muscular activity of the antagonist groups. And although there is evidence that demonstrates the benefits, it is found that most research projects do not have quantitative data to validate their results. The present review has implications for the practice of neurological hand rehabilitation and physical therapy, which can be summarized in the following aspects: Towards the implementation of exoskeletons directed to the functionality of fine and gross gripper following trauma or neurological condition in which the role of the physical therapist has to be directed in providing knowledge about the physiology of the hand, the ergonomic requirements of exoskeletons as an approach to the complementation of what can be obtained with the conventional treatment of Physical Therapy and be included in rehabilitation programs. Since the patient's adaptation to exoskeletons may vary depending on the pathology or neurological condition, an individualized evaluation adapted to the patient's needs is required for the design of exoskeletons, which implies the personalization of therapy with the implementation of these devices.

Finally, several suggestions for future work and new hypotheses can be made, such as: long-term studies to measure the results and benefits of using exoskeletons in rehabilitation processes, sustainability evaluations with them, as well as their functional capacity, comparisons between exoskeleton designs with specific features and functions that give us standard implementations for each condition.

Methodology

For the present literature review, a search for articles was conducted in the following databases, Dialnet, Redalyc, PubMed, Google Scholar and Scielo. The following inclusion criteria were applied: published articles that their year of publication was from 2018 to date, included the keywords and descriptors: exoskeleton, rehabilitation, disability, benefits and hand. Randomized clinical trials, meta-analyses, case-controls, cohort studies, systematic reviews, and literature reviews were included in the search. Studies were excluded if their year of publication was less than 2018 and if they did not contemplate the keywords or were not complete or available.

Results

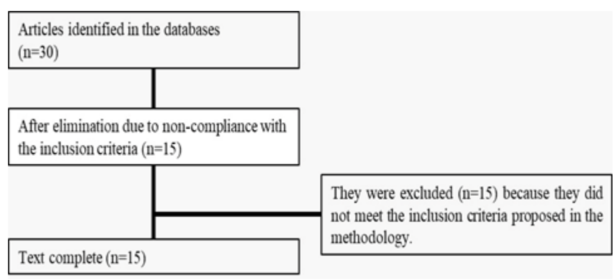

Figure 1 Analysis of articles
Source: Prepared by the authors

After the review of the analyzed literature, it is shown that 47% of the selected articles correspond to the design and development of an exoskeleton prototype for the hand or arm, 33% are experimental studies and the remaining 20% correspond to bibliographic reviews. Of the total of bibliographies, 93.3% of the investigations describe the benefits and functionality of exoskeletons in rehabilitation and the performance of manual activities. Only one article discards the benefits of the use of robots.

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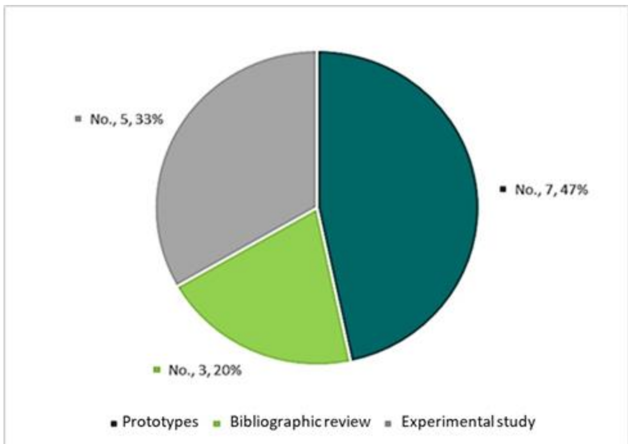

Graphic 1 Percentage of the number of studies analyzed
Source: Prepared by the authors

Conclusions

In this literature review regarding the benefits of exoskeletons in hand rehabilitation process and after the analysis of the analyzed information, a positive result was obtained in terms of applications, functionality, ergonomics and improvement in physical abilities of strength, precision in the fine and coarse gripper in which exoskeletons are presented as a promising implementation for hand rehabilitation in terms of mobility recovery. Estimation of different types of exoskeletons reveals their plurality in terms of design, features and functionalities.

Practice protocols and recommendations for exoskeleton performance require continuous estimation and individualized tailoring of protocols according to the disease to maximize application outcomes to exoskeleton performance and benefits. No articles have been found that more accurately analyze and evaluate application outcomes in patients with hand rehabilitation in the face of the variety of devices available, however, contributions have been initiated for ergonomic improvements focused on exoskeleton design and functionality.

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Article

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Evaluation of the effects of biocompost based on sugarcane cachaza on soil physical properties

Evaluación de los efectos del biocompost a base de cachaza de caña de azúcar en las propiedades físicas del suelo

MOJICA-MESINAS, Cuitláhuac†, LORENZO-MÁRQUEZ, Habacuc, ACOSTA-PINTOR, Dulce Carolina* and WONG-ARGUELLES, Cynthia

Tecnológico Nacional de México – Instituto Tecnológico de Ciudad Valles, Carretera al Ingenio Plan de Ayala Km. 2, Colonia Vista Hermosa, C.P. 79010, Ciudad Valles, S.L.P.

ID 1st Author: *Cuitláhuac, Mojica-Mesinas* / **ORC ID:** 0000-0001-8585-8249, **Researcher ID Thomson:** T-3267-2018, **arXiv Author ID:** MOMC640319JF8, **CVU CONAHCYT ID:** 744041

ID 1st Co-author: *Habacuc, Lorenzo-Márquez* / **ORC ID:** 0000-0001-7060-6188, **Researcher ID Thomson:** HIZ-8756-2022, **CVU CONAHCYT ID:** 493043

ID 2nd Coauthor: *Dulce Carolina, Acosta-Pintor* / **ORC ID:** 0000-0003-0784-7039, **Researcher ID Thomson:** T-3349-2018, **arXiv Author ID:** DulceAcosta, **CVU CONAHCYT ID:** 626925

ID 3rd Co-author: *Cynthia, Wong-Arguelles* / **ORC ID:** 0000-0001-9637-5023, **arXiv Author ID:** CynthiaWong, **CVU CONAHCYT ID:** 171739

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Abstract

The study assessed the effects of sugarcane cachaza biocompost on soil physical properties in the Huasteca Norte. Significant improvements were observed in bulk density, real density, and porosity, indicating a more favorable soil structure with increased biocompost. Additionally, there was an increase in water retention percentage with the addition of biocompost. Organic matter analysis revealed notable differences among treatments, with Treatment T4 exhibiting the highest content. These results suggest the positive potential of biocompost in enhancing soil quality in the region. The discussion will focus on the relevance of these findings for sustainable agricultural practices and effective soil management in the Huasteca Norte, as well as potential implications for productivity and environmental sustainability in the region.

Biocompost, Soil, Sugarcane cachaza

Resumen

El estudio evaluó los efectos del biocompost de cachaza de caña de azúcar en propiedades físicas del suelo en la Huasteca Norte. Se observaron mejoras significativas en densidad aparente, densidad real y porosidad, indicando una estructura del suelo más favorable con el aumento del biocompost. Además, se destacó un incremento en el porcentaje de retención de agua con la adición de biocompost. El análisis de materia orgánica reveló diferencias notables entre tratamientos, con el tratamiento T4 mostrando el contenido más alto. Estos resultados indican el potencial positivo del biocompost en la mejora de la calidad del suelo en la región. La discusión se centrará en la relevancia de estos hallazgos para prácticas agrícolas sostenibles y la gestión efectiva de suelos en la Huasteca Norte, así como posibles implicaciones para la productividad y sostenibilidad ambiental en la región.

Biocompost, Suelo, Cachaza

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† Researcher contributing as first author.

* Correspondence to author (E-mail: dulce.acosta@tecvalles.mx)

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Introduction

With climate change emerging as one of the most pressing challenges of the 21st century, its significant impacts on food security and the sustainability of agricultural systems worldwide cannot be overlooked. Mexico, with its rich geographic diversity and historical dependence on agriculture, is immersed in the effects of climate change. Alterations in weather patterns, rising temperatures and the frequency of extreme weather events have exacerbated the vulnerability of Mexican agricultural systems, compromising the country's food security and economic stability.

This scenario manifests itself critically in the agricultural sector, where changes in climatic conditions can have devastating consequences for crop productivity and quality. Mexico's agricultural regions, including the Huasteca Norte in San Luis Potosí, face direct threats such as prolonged droughts, flash floods and changes in the availability of water resources. This reality underscores the urgent need to develop adaptive and mitigation strategies that strengthen the resilience of agricultural systems to climate change.

In particular, the Huasteca Norte region has experienced these problems, which demonstrate the exacerbated vulnerability of its agricultural fields, especially those dedicated to the cultivation of sugar cane (Saccharum officinarum L.). This crop, emblematic of the region, is not only crucial for the local economy but also for the national sugar industry.

In this context, the present article focuses on the evaluation of the effects of sugarcane pulp biocompost on the physical properties of the soil. Cachaza, a by-product of the sugar industry, is presented as a valuable resource that, when converted into biocompost, could offer significant benefits for improving soil resilience and counteracting the adverse effects of climate change on sugarcane fields in the Huasteca Norte region. To support this research, a comprehensive, evidence-based analysis was carried out to contribute to a holistic understanding of the challenges and potential solutions at the interface between climate change, agriculture and soil sustainability.

The present study proposes to address this need by assessing the effects of sugarcane cachaza-based biocompost on the physical properties of soil typical of the region. Cachaça, an abundant by-product of the sugar industry, has been identified as a promising source of nutrients and organic matter to improve soil quality (Senatore et al., 2023). The transformation of cachaza into biocompost not only presents a solution to sustainable industrial waste management, but also raises the possibility of strengthening the resilience of agricultural soil to climate stresses (Mahapatra et al., 2022).

The conceptual basis of this approach lies in the ability of compost to improve soil physical properties such as structure, water holding capacity and microbial activity (Smith et al., 2010; Lehmann et al., 2011). Previous studies have shown that the addition of compost to soil can improve soil structure, promote moisture retention and increase the availability of essential plant nutrients. In addition, compost can act as a buffer against extreme weather events, protecting soil health and promoting crop resilience (Pratap and Prabha, 2017).

Cachaza, in its composition, is rich in organic matter, an essential component for soil health. Organic matter acts as a source of carbon and energy for soil microorganisms, thereby promoting microbial activity and improving soil structure (Mahapatra et al., 2022; Smith et al., 2010). In addition, cachaza contains essential nutrients, such as nitrogen, phosphorus and potassium, which are essential for plant growth (Senatore et al., 2023; Lehmann et al., 2011). The presence of these nutrients makes cachaza a valuable resource for enriching the soil and improving the availability of nutrients for crops.

Four treatments were designed for this research, consisting of a mixture of typical soil and biocompost in varying proportions (10%, 20%, 30% and 40%), together with a negative control representing conditions without compost addition (Lehmann et al., 2011). These proportions were selected in order to systematically evaluate the effects of biocompost on the soil and to determine the optimal dosage to improve physical properties without causing adverse impacts.

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Methodology to be developed

Experimental design

The experimental design was carried out in the experimental field of the Environmental Research and Monitoring Laboratory of the Tecnológico Nacional de México, Campus Ciudad Valles. It was structured around the evaluation of four treatments with different proportions of biocompost based on sugar cane waste (10%, 20%, 30%, 40%) and a fifth treatment that represented the typical soil of the Northern Huasteca region in San Luis Potosí, used as a negative control. Each of the treatments, including the negative control, was replicated five times, distributing the replicates randomly in the experimental field. In this context, it is important to highlight that, according to Shrivas et al. (2023), organic amendments such as biocompost can have a significant impact on the diversity of the rhizospheric bacterial community, a crucial aspect for soil health and crop growth. These findings underline the relevance of our study in the broader context of research on soil sustainability and agriculture.

The scion technique was implemented to simulate realistic agricultural conditions. It consisted of taking healthy segments of sugarcane and planting them at a uniform depth of 30 cm in the soil of the cultivation boxes. This technique facilitated the germination and uniform growth of the sugar cane, allowing an accurate assessment of the effects of the biocompost on the crop.

Continuous monitoring was extended over 30 days, during which time the progress of the crop was closely monitored and observable changes in the physical properties of the soil were recorded. This experimental design, implemented in the experimental field of the Environmental Research and Monitoring Laboratory, provides a robust framework for evaluating the effects of biocompost in a controlled environment representative of local conditions in the Northern Huasteca region.

Study material: biocompost composition

In this study, biocompost made from sugarcane cachaza, a by-product obtained through collaboration between the Environmental Research and Monitoring Laboratory of the Tecnológico Nacional de México, Campus Ciudad Valles, and the Asociación de Cañeros CNPR del Ingenio Plan de San Luis, was used. This by-product was subjected to an open-pit composting process, a technique also employed by Saengsanga and Noinumsai (2023), who experimented with water hyacinth and spent coffee grounds as biocompost feedstocks. Their study demonstrated the feasibility and diversity of organic by-products in biocompost production, ensuring controlled biological decomposition. During the process, optimal conditions of temperature (50-60 °C) and relative humidity (50-60%) were maintained, facilitating microbial activity and effective decomposition of organic matter. This semi-industrial collaboration ensured a biocompost of representative quality, reflecting the usual practices of the local sugar industry.

Detailed monitoring of the composting process ensured the consistency and quality of the biocompost applied in the treatments. This material, rich in pulp and bagasse, became a valuable soil amendment. Its open-pit production not only highlights its viability and efficiency, but also its alignment with sustainable agricultural practices. This approach not only makes efficient use of bagasse as a valuable resource, but also addresses the responsible management of industrial waste.

The use of this biocompost in the study treatments ensures that the results obtained are directly applicable to real agricultural scenarios, providing relevant and practical information for the implementation of sustainable strategies in the Huasteca Norte region.

Measurement of parameters

In the evaluation of soil physical properties, accuracy and validity of measurements are essential. To determine the True Soil Density, the cylinder method of known volume was used, according to ASTM D7928-17. Bulk Density was evaluated using the known volume cylinder method, following the guidelines established by ASTM D5550-18. Soil Porosity was determined by the saturation and weighing method, based on ISO 11274:2014. Water Retention was analysed using the Richards pressure table method, according to ASTM D6836-16. Soil Organic Matter was quantified using the Walkley-Black method supported by ISO 14235:1998. This method, based on the oxidation of organic carbon, provides an accurate estimate of soil organic matter, crucial for understanding soil fertility and long-term health. The implementation of these methods guarantees the analytical quality, consistency and validity of the measurements, ensuring the robustness of the results obtained in this study.

Statistical analysis

For the evaluation of significant differences between treatments, a robust statistical approach was implemented. Initially, normality (Shapiro-Wilk) and homogeneity of variance (Bartlett) tests were performed to confirm the normal distribution of the data and the equality of variances between groups, respectively.

Subsequently, one-way analysis of variance (ANOVA) was applied for each soil property evaluated: Apparent Density (AD), True Density (RD), Porosity (PR), Water Retention Percentage (WR) and Soil Organic Matter Percentage (SOM). We used Tukey's test to perform multiple comparisons of means, identifying significant differences between treatments.

All statistical analyses were carried out at a significance level of 0.05 ($\alpha = 0.05$) to determine the presence of significant statistical differences. In addition, we employed specialised statistical software, specifically Google Colab and Python, to ensure the accuracy and reliability of the results. This statistical approach provided a rigorous and informed assessment of variations in soil properties between treatments, allowing conclusions to be supported by statistical evidence.

Results

Statistical analyses of soil physical properties reveal distinctive patterns among the treatments in the experiment, where the impact of sugarcane cane biocompost on soil in the Huasteca Norte was assessed. This aligns with the findings of Meena and Pradhan (2023), who reported that industrial biocompost derived from rubbish improves soil organic carbon fractions and CO2 biosequestration. Also, parallel research by EL Moussaoui, Ainlhout and Bouqbis (2023) highlighted positive effects of biocompost on alfalfa growth and productivity, demonstrating the efficacy of biocompost in different agricultural contexts. For the Control treatment (T0), which represents the typical soil of the region, an average bulk density (DA) of 1.128 g/cm^3, true density (RD) of 1.211 g/cm^3 and porosity (PR) of 6.8% were observed. As the proportion of biocompost increased in treatments T1 (10%), T2 (20%), T3 (30%), and T4 (40%), significant changes in these physical properties were observed, with values of DA, DR and PR varying coherently with the increase in biocompost, as shown in Figures 1, 2 and 3.

The analysis of variance (ANOVA) and Tukey's tests highlight statistically significant differences between treatments for these properties ($p < 0.05$), showing the positive impact of biocompost on the physical structure of the soil. In particular, it is observed that the T4 treatment presents a lower bulk density (0.905 g/cm^3), lower real density (1.038 g/cm^3) and higher porosity (12.8%), indicating substantial improvements in soil structure, according to the data presented in Figures 1, 2 and 3.

Regarding the percentage of water retention (ret_water), significant variations were observed between treatments, with the T1 treatment standing out with 64.4% and the T0 with 52.3%. These data are presented in Figure 4.

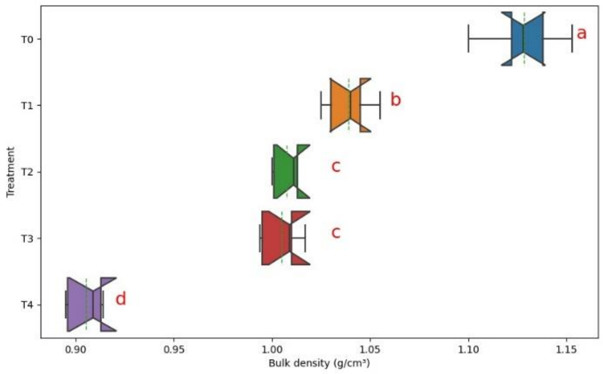


Figure 1 Bulk density (g/cm^3)
Source: Own, Google Colab-Python

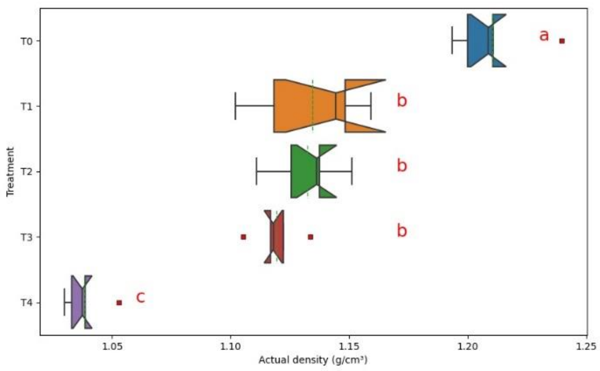


Figure 2 Actual density (g/cm^3)
Source: Own, Google Colab-Python

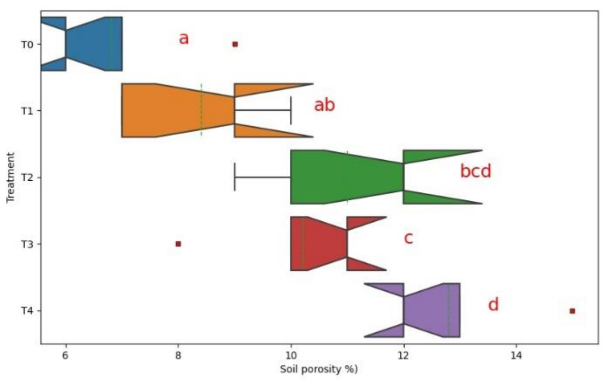


Figure 3 Soil porosity (%)
Source: Own, Google Colab-Python

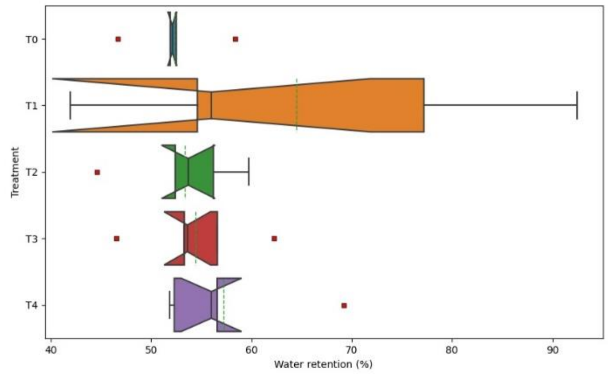
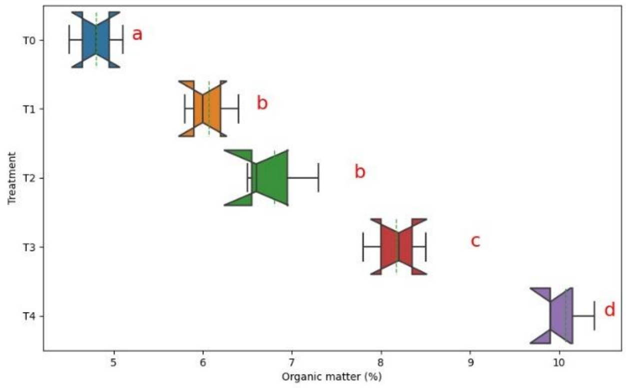


Figure 4 Water retention (%)
Source: Own, Google Colab-Python

Figures 1 to 4 present boxplots illustrating variations in soil physical properties under different biocompost treatments. In each graph, the letters (a, b, c, d, e) indicate significant differences between treatments, providing a visual representation of variations in bulk density, true density, soil porosity and water retention.

When analysing the organic matter content in our treatments, we observed significant variations, which highlights the potential of biocompost to enrich the soil. This phenomenon aligns with the findings of Pradhan and Meena (2023), who highlighted a considerable impact of biocompost on soil nutrient dynamics. This observation is particularly relevant to our study, suggesting that the noted improvements in soil quality could be directly related to changes in nutrient availability and balance, key factors for soil health and productivity. In our results, the T4 treatment showed the highest percentage of soil organic matter (SOM) with 8.3%, in contrast to T0 which showed the lowest with 4.4%. These differences are illustrated in Figure 5, highlighting the variations in organic matter content between the different treatments.



Letters (a, b, c, d indicate significant differences between treatments, providing a visual representation of the variations in % organic matter.

Figure 5 Organic matter (%)
Source: Own, Google Colab-Python

ANOVA and Tukey's test confirm significant differences between treatments for the variable OM ($p < 0.05$). These detailed results highlight the differential response of the soil to different proportions of biocompost, providing valuable evidence of the benefits of this organic amendment on the physical and chemical properties of the soil of the Huasteca Norte. These findings have crucial implications for the design of sustainable agricultural practices and effective soil management in the region.

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Conclusions

In conclusion, the results of this research highlight the transformative potential of biocompost derived from sugarcane cachaza in substantially improving soil physical properties in the Northern Huasteca region. The reduction of bulk and real density, the significant improvement in porosity and water retention, as well as the enrichment of organic matter content, validate the effectiveness of this organic amendment. These findings, in line with the stated objectives and hypotheses, not only contribute to the scientific understanding of sustainable agricultural practices, but also offer practical and ecological insights.

The practical implications of this study suggest that the application of biocompost can not only increase crop productivity, but also has the potential to improve the resilience of agricultural systems to extreme weather events. Increased soil organic matter not only contributes to soil fertility, but can also support microbial biodiversity and long-term soil health. However, it is crucial to recognise the limitations of the study, such as the sample size and the duration of the experiment. More extensive and detailed future research is required to consolidate and extend these results, which will strengthen the scientific basis for effective implementation of sustainable agricultural practices in regions vulnerable to climate change and soil degradation. This study not only supports the viability of biocompost as a strategy for sustainable soil management, but also underscores the importance of continued research in promoting agricultural resilience and mitigating adverse environmental impacts.

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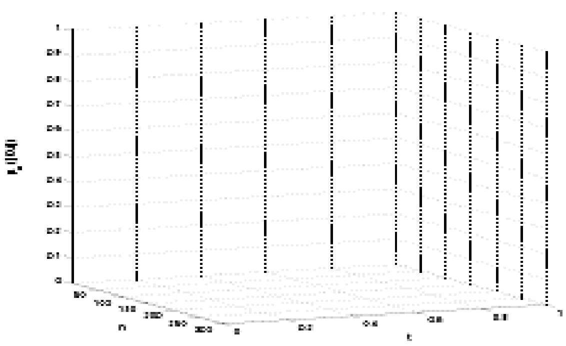

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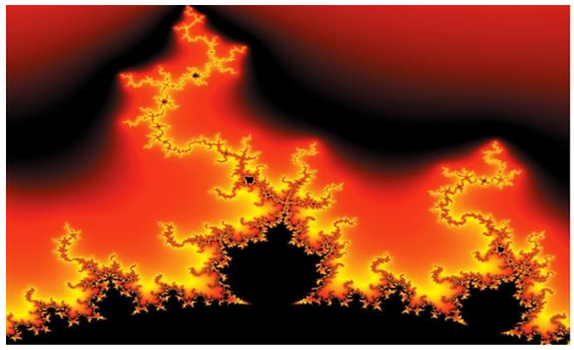

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