Colegio de Postgraduados

Economic impact of soil bioremediation with sugarcane monoculture using Artificial Intelligence

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ABSTRACT

Objective: Develop an intelligent system capable of predicting the best bioremediation strategy at the laboratory scale for a Vertisol soil sample with sugarcane monoculture, to achieve a target of 90 tons per hectare, with the aim of achieving an economic impact on sugarcane producers in the high mountains of the State of Veracruz.

Design/Methodology/Approach: The following soil bioremediation techniques are used: Bioremediation using *Bacillus megaterium*, bioremediation using vermicompost to promote bioaugmentation, and bioremediation using *Azospirillum brasilense* + *Pantoea dispersa*; to estimate the economic impact of using an intelligent system system for soil bioremediation with sugar cane monoculture.

Results: An intelligent system was developed for soil bioremediation, with the goal of achieving 90 tons of sugarcane per hectare, thus achieving a significant economic impact on sugarcane producers in the High Mountains Region of the State of Veracruz.

Limitations/Implications: To carry out the tests for each bioremediation, samples of five Vertisol soils from the High Mountain Region of Veracruz were placed, with different degrees of degradation and whose chemical characterization is already known for each soil type. A control sample was used for each sample, which was not modified in any way, but was simply placed under the same environmental and irrigation conditions as the other samples.

Findings/Conclusions: Software was developed that analyzes the physicochemical properties of the soil in order to recommend the most feasible bioremediation strategy to the user, with the goal of achieving 90 tons/hectare, representing an economic improvement of almost 30% for sugarcane producers.

Keywords: Economic impact, soil bioremediation, sugarcane monoculture, artificial intelligence.

INTRODUCTION

Sugar cane is the most productive crop worldwide, and Mexico ranks as the sixth largest producer of sugar and sugar cane in the world (Sentíes-Herrera *et al.*, 2019). The sugarcane production system generates more than two million direct and indirect jobs and is carried

out in 15 states and 258 municipalities (Sentíes-Herrera *et al.*, 2017). This agro-industry contributes 1.98% of manufacturing GDP, 16.44% of agricultural GDP, and 8.29% of food industry GDP (Enriquez-Poy, 2016). Although the area planted has remained stable with slight increases, raw material production is trending downward, possibly due to widespread soil deterioration, the effects of global climate change, and rising prices for production inputs, among other factors. It should be noted that among agri-food crops, sugarcane has the highest yields, with a global average of over 70 t ha^{-1}, which can be increased through genetic improvement and agronomic management, such as precision agriculture (Gómez-Merino *et al.*, 2017). According to García Chávez (2009, 2008, and 1997), in order to increase sugar production by 20% to meet domestic demand, the harvestable area would have to be increased by 18.6%, or a 21% increase in field yield or a 24% increase in factory yield would have to be achieved. Therefore, it is contradictory for Mexico to attempt to promote a diversification project, such as biofuels, when the problem is the recovery of productivity levels in the sugarcane field, which are trending downward. (Aguilar-Rivera, 2012) (Aguilar-Rivera *et al.*, 2011).

Several studies indicate that intensive sugarcane monoculture, excessive use of agrochemicals, and practices such as burning degrade soil quality, reduce organic matter, and cause salinity and erosion. In addition, economic analyses highlight that chemical fertilizers can account for up to 27% of production costs, affecting profitability, while other research highlights that sustainable practices such as the use of biofertilizers and the incorporation of crop residues can improve soil health and increase long-term yields, resulting in indirect economic benefits. and that bioremediation alternatives are presented as more economical, less invasive, and environmentally friendly methods compared to physical-chemical treatments (Tobón *et al.*, 2011) (Farrell *et al.*, 2010) (Rodríguez *et al.*, 2007) (Tobón *et al.*, 2011).

In summary, although there is clear recognition of the need to remediate degraded sugarcane soils and the inherent benefits of bioremediation, there is clearly an opportunity to develop low-cost technology that can determine the physical and chemical characteristics of the soil and predict the best bioremediation strategy using artificial intelligence.

Therefore, at the Orizaba Institute of Technology, located in the High Mountains region of the state of Veracruz, inventions have been developed to facilitate soil characterization, focusing specifically on the sugarcane sector in the High Mountains of Veracruz. Specifically, a low cost portable device was developed to determine the physical-chemical variables EC, K, Ca, Mg, and Na, using a capacitive sensor in soils dedicated to sugarcane production, through the use of integrated spectroscopy techniques and the integration of five neural network algorithms, to enable the determination of these variables with supervised artificial intelligence. This invention was patented by the Mexican Institute of Industrial Property (IMPI), with Patent Number: MX 399884 B (Sandoval González *et al.*, 2023). This invention was experimentally validated for vertisols with sugarcane production in the High Mountains Region of Veracruz (Landeta Escamilla *et al.*, 2023).

Therefore, based on low-cost portable technology to determine the physicochemical characteristics of soil, the objective of this research is to develop an intelligent system capable of predicting the best bioremediation strategy at the laboratory scale for a Vertisol soil sample with sugarcane monoculture, in order to achieve a target of 90 tons per hectare, with the aim of achieving an economic impact on sugarcane producers in the high mountains of the State of Veracruz.

MATERIALS AND METHODS

To perform laboratory scale tests for each bioremediation, samples of five Vertisol soils from the High Mountain Region of Veracruz were placed, with different degrees of degradation and whose chemical characterization is already known for each soil type. A control sample was used for each sample, which was not modified in any way, but was placed under the same environmental and irrigation conditions as the other samples. The bioremediation techniques used in the experiment were:

1. Bioremediation using *Bacillus megaterium*
2. Vermicomposting to promote bioaugmentation
3. Bioremediation using *Azospirillum brasilense* + *Pantoea dispersa*

Once established, an initial measurement was taken and changes in each system were subsequently evaluated monthly for 8 months. This information will be used for the AI system. It is important to note that all studies analyzing the physical and chemical properties of the soil were carried out using the intelligent capacitive spectroscopy system for determining physical and chemical properties developed in this research project. The final results obtained have made it possible to generate software that can make recommendations for soil remediation based on these three bioremediation proposals.

Bioremediation using *Bacillus megaterium*

To carry out the experiment, brick containers measuring 60 cm wide, 2 m long, and 30 cm deep were used, separated into four divisions in which four different samples of Vertisol-type soils were deposited. *Bacillus megaterium* was added to all four soils.

Table 1 shows a statistical analysis of the initial properties (pH, P, K, Ca, Mg, Na, conductivity, and nitrate nitrogen) of the soils used for bioremediation. It also shows the final values of the variables pH, N, P, and K, which were the properties that underwent the most significant changes in the experiment.

Table 1. Statistics of the initial and post-bioremediation physicochemical properties of soils.

	pH soil	P	K	Ca	Mg	Na	Conduc-tivity	N-NO_3	pH	N	P.1	K.1
mean	6.060000	58.800000	208.200000	3289.800000	396.000000	16.600000	0.218000	28.200000	5.860000	28.500000	56.900000	171.200000
std	0.176126	9.967293	24.722129	531.934543	52.737316	7.41207	0.02814	6.496467	0.176126	6.496467	9.967293	24.722129
Min	5.900000	42.000000	183.000000	2253.000000	311.000000	11.000000	0.170000	20.000000	5.700000	20.300000	40.100000	146.000000
25%	6.000000	55.000000	192.000000	3411.000000	371.000000	12.000000	0.210000	22.000000	5.800000	22.300000	53.100000	155.000000
50%	6.000000	60.000000	200.000000	3488.000000	404.000000	14.000000	0.220000	29.000000	5.800000	23.300000	58.100000	163.000000
75%	6.000000	68.000000	213.000000	3637.000000	431.000000	15.000000	0.240000	33.000000	5.800000	33.300000	66.100000	176.000000
max	6.400000	69.000000	253.000000	3660.000000	463.000000	31.000000	0.250000	37.000000	6.200000	37.300000	67.100000	216.000000

Bioremediation using vermicomposting

To carry out the experiment, brick containers measuring 60 cm wide, 2 m long, and 30 cm deep were used, separated into four divisions in which four different samples of Vertisol soil from the High Mountain Region of Veracruz were deposited. The vermicompost treatment was applied to the four soil samples, knowing in advance their physicochemical properties using the intelligent system for estimating physicochemical parameters developed in this research project, which was mentioned in previous reports.

Table 2 shows a statistical analysis of the initial properties (pH, P, K, Ca, Mg, Na, conductivity, and nitrate nitrogen) of the soils used for bioremediation. It also shows the final values of the variables pH, N, P, and K, which were the properties that underwent the most significant changes in the experiment

Azospirillum brasilense + Pantoea dispersa

To carry out the experiment, brick containers measuring 60 cm wide, 2 m long, and 30 cm deep were used, separated into four divisions in which four different samples of Vertisol soil were deposited. The *Azospirillum brasilense* + *Pantoea dispersa* treatment was applied to the four soil samples, knowing in advance their physicochemical properties using the intelligent system for estimating physicochemical parameters developed in this research project, which was mentioned in previous reports.

Table 3 shows a statistical analysis of the initial properties (pH, P, K, Ca, Mg, Na, conductivity, and nitrate nitrogen) of the soils used for bioremediation. It also shows the

Table 2. Statistics of the initial and post-bioremediation physicochemical properties of soils.

	pH soil	P	K	Ca	Mg	Na	Conduc-tivity	N-NO_3	pH	N	P.1	K.1
mean	6.360000	28.000000	88.400000	2307.000000	383.600000	41.200000	0.162000	27.200000	6.160000	27.500000	26.100000	51.400000
std	0.627922	9.236131	23.721169	820.260536	171.084872	20.378059	0.041601	8.141604	0.627922	8.141604	9.236131	23.721169
Min	5.700000	17.000000	60.000000	1321.000000	210.000000	26.000000	0.110000	17.000000	5.500000	17.300000	15.100000	23.000000
25%	5.800000	20.000000	70.000000	1375.000000	212.000000	27.000000	0.120000	21.000000	5.600000	21.300000	18.100000	33.000000
50%	6.100000	27.000000	80.000000	2712.000000	352.000000	27.000000	0.180000	25.000000	5.900000	25.300000	22.100000	43.000000
75%	7.000000	34.000000	113.000000	2792.000000	495.000000	48.000000	0.200000	35.000000	6.800000	35.300000	30.000000	76.000000
max	7.200000	42.000000	119.000000	3335.000000	649.000000	78.000000	0.220000	38.000000	7.000000	38.300000	40.100000	82.000000

Table 3. Statistics of the initial and post-bioremediation physicochemical properties of soils.

	pH soil	P	K	Ca	Mg	Na	Conduc-tivity	N-NO_3	pH	N	P.1	K.1
mean	6.328000	28.240000	120.520000	2718.640000	571.920000	42.224000	0.159600	23.200000	6.244000	24.446000	41.122000	165.140000
std	0.658396	21.824495	83.296922	933.180831	351.639881	56.033003	0.054058	9.133924	0.694632	7.402901	19.434172	21.202628
Min	5.200000	2.000000	46.000000	713.000000	102.000000	8.000000	0.060000	7.000000	5.200000	15.200000	14.000000	148.000000
25%	5.900000	9.000000	48.000000	2253.000000	311.000000	12.000000	0.130000	19.000000	5.700000	19.000000	15.000000	155.000000
50%	6.400000	19.000000	64.000000	2491.000000	401.000000	23.000000	0.170000	22.000000	6.200000	22.000000	40.100000	158.000000
75%	7.000000	55.000000	200.000000	3637.000000	755.000000	33.000000	0.200000	31.000000	7.000000	35.300000	58.100000	163.000000
max	7.300000	60.000000	253.000000	3660.000000	1257.000000	178.000000	0.240000	37.000000	7.000000	37.300000	72.000000	216.000000

final values of the variables pH, N, P, and K, which were the properties that underwent the most significant changes in the experiment.

Intelligent system for soil bioremediation

An Intelligent System for soil bioremediation was developed, in order to recommend the most feasible bioremediation strategy that could be used to achieve a target of 90 tons/ha, using three bioremediation techniques with the aim of understanding the behavior and changes in the physicochemical properties of the soil. Samples of five Vertisol soils from the High Mountain Region of Veracruz, with different degrees of degradation, were selected with the aim of creating a model based on artificial intelligence techniques that can estimate how the values of the physicochemical properties of the soil will be modified through the use of a certain bioremediation technique.

The methodology implemented for the software design was as follows:

1. Use of the decision tree algorithm to estimate which bioremediation technique is most appropriate based on the physicochemical parameters of the soil to be restored.
2. Use of Artificial Neural Networks to estimate the levels of pH, N, P, and K that can be achieved through the implementation of the recommended bioremediation.

Figure 1 shows the block diagram of the software for estimating bioremediation in vertisol soils with sugarcane cultivation. It can be seen that the values from the capacitive spectroscopy sensor are used as input data, and the neural network was trained using the database with the results obtained with the three bioremediation methods. The network output shows the estimated values to be obtained if the recommended bioremediation is used.

The mean square errors obtained between the actual values and those estimated by the neural network are: P=5.52 ppm, pH=0.74, Na=2.91 ppm, N=2.35 ppm, Mg=5.68 ppm, K=7.03 ppm, EC=0.0097 dS/m, and Ca=213 ppm. Setting the maximum value of

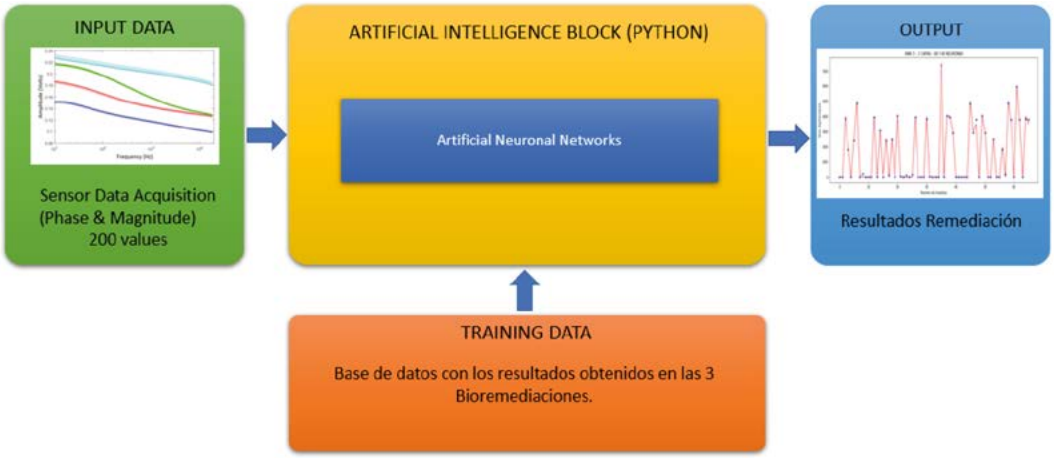

Figure 1. Block diagram of the software for estimating bioremediation.

each element (P, pH, Na, N, Mg, K, EC, and Ca) as the maximum range, the following error percentages were obtained: P=4.90%, pH=8.52%, Na=8.43%, N=4.24%, Mg=0.93%, K=2.44%, EC=3.81%, and Ca=3.91%.

Figure 2 shows the diagram resulting from the use of the decision tree algorithm. This algorithm is capable of segmenting and classifying information. Therefore, upon receiving information on the pH, P, K, Mg, Na, electrical conductivity, and nitrate nitrogen properties of the soil, the algorithm is able to recommend the best bioremediation technique according to the soil properties.

RESULTS AND DISCUSSION

Large-scale bioremediation faces several technical, logistical, and environmental challenges that limit its effectiveness and adoptability. This type of intervention is often a slow process, especially in in-situ applications, as it depends on natural biological activity and specific environmental conditions —such as pH, temperature, humidity, and nutrients— which cannot always be optimally maintained, consistent with the work reported by Romantschuk *et al.* (2023). Furthermore, there is uncertainty regarding the complete degradation of certain contaminants, as some compounds may resist the process or generate even more toxic byproducts. Added to this are the potential secondary ecological impacts, such as alterations to the local ecosystem due to the addition of microorganisms or nutrients.

Therefore, the experimentation carried out in this research was conducted at a laboratory scale, and its scalability will be addressed in future work. The results and discussion of the laboratory-scale bioremediation carried out in this research are presented below.

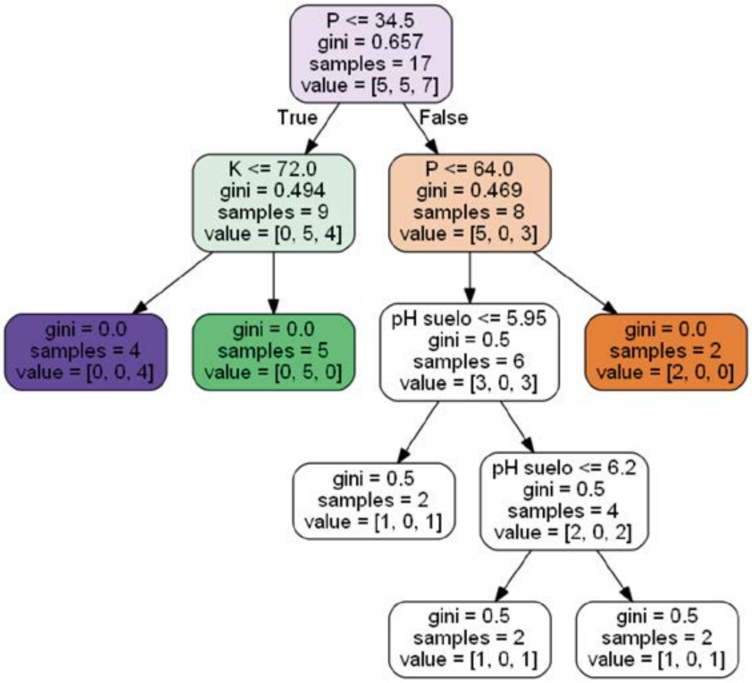

Figure 2. Decision tree algorithm.

Bioremediation using *Bacillus megaterium*

After eight months of experimentation to characterize bioremediation using *Bacillus megaterium*, it was determined that there was a small decrease in pH value of −0.35, on average, in the four soil samples; which is consistent with what was reported by Njoku *et al*. 2020). In addition, an increase in nitrogen of approximately +6.4 ppm was detected on average in the four soil samples. Therefore, it was determined that *Bacillus megaterium* should be used in soils whose initial nitrogen value is lower than the optimal value recommended for sugarcane cultivation, since the use of *Bacillus megaterium* will increase the nitrogen level in the soil; which is consistent with what was reported by (He *et al*., 2023). Additionally, an increase in phosphorus of approximately +6.8 ppm on average in the four soil samples, so it was determined that *Bacillus megaterium* should be used in soils whose initial phosphorus value is lower than the optimal value recommended for sugarcane cultivation, since the use of *Bacillus megaterium* will increase the phosphorus level in the soil; which is consistent with what was reported by (Ramos *et al*., 2023). Finally, a decrease in potassium was detected, approximately −17.3 ppm, on average, in the four soil samples. It was therefore determined that *Bacillus megaterium* should be used in soils whose initial potassium value is higher than the optimal value recommended for sugarcane cultivation, as the use of *Bacillus megaterium* will decrease the potassium level in the soil.

Bioremediation using vermicompost

After eight months of experimentation to characterize bioremediation using vermicompost, it was determined that there was an increase of +0.48 in the pH value, on average, in the four soil samples; which is consistent with what was reported by (Tito *et al*., 2024). In addition, an increase in nitrogen of approximately +4.65 ppm was detected on average in the four soil samples. Therefore, it was determined that vermicompost should be used in soils whose initial nitrogen value is lower than the optimal value recommended for sugarcane cultivation, since the use of vermicompost will increase the nitrogen level in the soil; which is consistent with what was reported by (Huda *et al*., 2024). Additionally, an increase in phosphorus of approximately +5.35ppm on average in the four soil samples, so it was determined that vermicompost should be used in soils whose initial phosphorus value is lower than the optimal value recommended for sugarcane cultivation, since the use of vermicompost will increase the phosphorus level in the soil; which is consistent with what was reported by (Busato *et al*., 2021). In addition, an increase in potassium of approximately +28.26 was detected, on average, in the four soil samples. So, it was determined that vermicompost should be used in soils whose initial potassium value is lower than the optimal value recommended for sugarcane cultivation, since the use of vermicompost will increase the potassium level in the soil; which is consistent with what was reported by (Pierre-Louis *et al*., 2021).

Bioremediation using *Azospirillum brasilense* + *Pantoea dispersa*

After eight months of experimentation to characterize bioremediation using *Azospirillum brasilense* + *Pantoea dispersa*, it was determined that in two of the soil samples there was virtually no change in pH, while in the other two soil samples there was an average decrease of −0.23 in pH value; which is consistent with (Schoebitz *et al.*, 2014), who reported that there was no significant change in soil pH with this bioremediation strategy, but there was a significant increase in phosphorus and potassium in the soil, which coincides with the experimental results obtained in the present study, in which an increase was obtained in nitrogen of approximately +7.88 ppm, on average, was detected in the four soil samples, Therefore, it was determined that *Azospirillum brasilense* + *Pantoea dispersa* should be used in soils whose initial nitrogen value is lower than the optimal value recommended for sugarcane cultivation, since the use of *Azospirillum brasilense* + *Pantoea dispersa* will increase the nitrogen level in the soil. Additionally, an increase in phosphorus of approximately +4.29 ppm was detected, on average, in the four soil samples. So it was determined that *Azospirillum brasilense* + *Pantoea dispersa* should be used in soils whose initial phosphorus value is lower than the optimal value recommended for sugarcane cultivation, since the use of *Azospirillum brasilense* + *Pantoea dispersa* will increase the phosphorus level in the soil. Finally, an increase in potassium of approximately +31.41 was detected, on average, in the four soil samples, so it was determined that *Azospirillum brasilense* + *Pantoea dispersa* should be used in soils whose initial potassium value is lower than the optimal value recommended for sugarcane cultivation, since the use of vermicompost will increase the potassium level in the soil.

Experimental testing of the developed system

A laboratory-scale test of the system developed in this project was conducted to determine the optimal bioremediation strategy and to predict the values achievable with said strategy. A brick container 60 cm wide, 2 m long, and 30 cm deep was used, into which a sample of Vertisol-type soil from a sugarcane monoculture was deposited. This sample presented initial values of pH 5.9, nitrogen at 20.17 ppm, phosphorus at 28.23 ppm, and potassium at 110.32 ppm, which are significantly below the ideal values required to reach the target of 90 tons per hectare.

Figure 3 shows the graphical interface created in LabVIEW + Python for estimating bioremediation parameters. The software obtains data from a portable device that was developed to determine the physical-chemical variables EC, K, Ca, Mg, and Na, using a capacitive sensor in soils dedicated to sugarcane production, through the use of integrated spectroscopy techniques and the integration of five neural network algorithms, to enable the determination of these variables with supervised artificial intelligence, which serves as input parameters for the decision tree algorithms and neural networks focused on estimating bioremediation parameters. On the one hand, the decision tree aims to determine the best bioremediation method according to the current physicochemical properties of the soil, and the neural networks, which were programmed in Python with Keras, TensorFlow, and Sci-kit learn libraries, were used to estimate the bioremediation parameters, giving us a future projection of the pH, N, P, and K levels.

Figure 3 shows that, based on the physicochemical properties of the soil sample used for this test, the bioremediation strategy recommended by the developed system was vermicomposting. Furthermore, the predicted pH, N, P, and K values to be obtained after vermicomposting were 6.6, 27.13 ppm, 34.26 ppm, and 139.17 ppm, respectively.

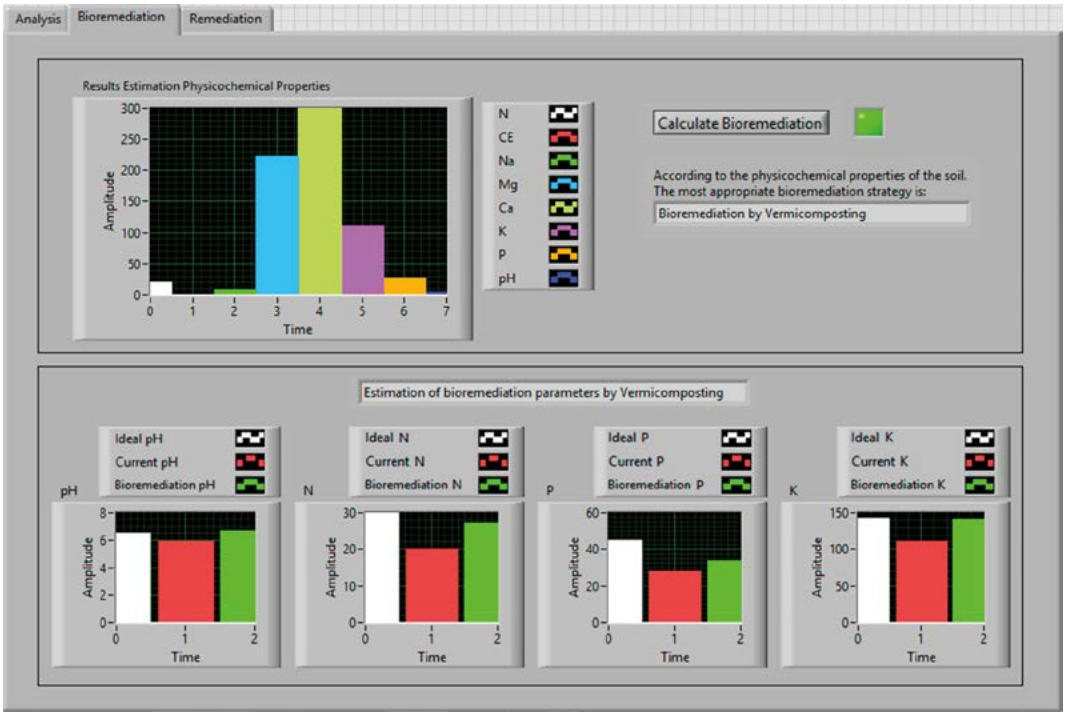

Figure 3. Graphical interface for estimating bioremediation parameters.

It is important to highlight that the results of the system developed in this project represent an innovative contribution to the use of AI to determine the best bioremediation strategy for Vertisol soils in the High Mountains of Veracruz, Mexico. This system could be adapted for the bioremediation of other soil types. Several programs in the literature utilize AI for other soil-related applications, such as Plantix, Crospin, and Soilgrids.

In (Siddiqua *et al.*, 2022), the authors evaluate Plantix and point out that it is not a complete solution for soil detection, diagnosis, and treatment, as it is a tool designed primarily to diagnose pests, diseases, and nutritional deficiencies in plants through AI analysis of photographs of symptoms present in crops. Therefore, Plantix is not capable of recommending soil bioremediation techniques. On the other hand, Cropin is a global agricultural technology company that offers digital and AI-based solutions for agriculture, helping to prevent soil degradation and optimize soil management for sustainable agricultural production, but it does not offer recommendations for the remediation of soils that are already severely degraded or contaminated. For its part, SoilGrids generates global-scale soil property maps with medium spatial resolution (250 m cells), using advanced machine learning methods to develop the necessary models, but many regions of the world are poorly sampled, such as boreal zones, mountainous areas, Africa, parts of Asia, and Latin America (Poggio *et al.*, 2021). This shows that SoilGrids is only a global soil database and does not offer recommendations for the best strategies for soil bioremediation, as does the system developed in this research.

In addition, software was developed that analyzes the physicochemical properties of the soil in order to recommend the most feasible bioremediation strategy that could be used to achieve a target of 90 tons/ha, representing an economic improvement of almost 30% for sugarcane producers, compared to the 70 tons/ha reported by (Sentíes-Herrera *et al.*, 2017).

CONCLUSIONS

An intelligent system was developed, capable of predicting the best bioremediation strategy at the laboratory scale for a Vertisol soil sample with sugarcane monoculture, to achieve a target of 90 tons per hectare, with the aim of achieving an economic impact on sugarcane producers in the high mountains of the State of Veracruz.

The economic impact of soil bioremediation with sugarcane monoculture can be assessed from different perspectives. It can increase productivity by improving yields per hectare, reduce costs by decreasing dependence on synthetic inputs, recover degraded land, and prevent economic losses associated with problems such as salinity and soil degradation. In addition, it strengthens the competitiveness of the sugar sector and can generate social and environmental benefits by improving crop sustainability, although it requires a significant initial investment that must be evaluated through a cost-benefit analysis considering the local context, soil conditions, crop management, and market prices, as well as the possibility of accessing subsidies or tax incentives. It can be complemented by sustainable strategies such as green sugarcane planting (without burning) to reduce environmental impact and improve soil quality.

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SUPPLEMENTARY MATERIAL

Data used to train the AI models are available upon request.

ETHICAL CONSIDERATIONS

No human subjects or sensitive data were involved in this research.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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