
DETECTION OF VIBRATION ANOMALIES IN MACHINERY USING LOW-COST MEMS SENSORS

VIBRATION ANOMALY DETECTION IN MACHINERY USING LOW-COST MEMS SENSORS

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Abstract-- This paper evaluated the feasibility of the low-cost MPU6050 inertial sensor for measuring vibrations in academic and industrial contexts. A data acquisition system was implemented using the MPU6050 sensor connected to an Arduino UNO board via the I²C bus to monitor vibration in a machine under test—in this case, a 3D printer. Acceleration data was collected at a frequency of 20 Hz and analyzed using the root mean square (RMS) value and crest factor (cf) to identify differences between normal and abnormal operating conditions.

The results showed that the measurements obtained with the sensor allow the identification of abnormal operating states derived from the detection of vibration anomalies. It was concluded that the MPU6050 sensor is a viable and economical alternative in preventive monitoring and experimental research applications under controlled conditions. However, the inherent limitations of the sensor in terms of resolution, dynamic range, and calibration must be considered.

Keywords-- MPU6050, accelerometer, low-cost sensors, vibration measurement, condition monitoring.

Abstract-- This work evaluated the feasibility of the low-cost MPU6050 inertial sensor for vibration measurement in academic and industrial settings. A data acquisition system was implemented using the MPU6050 sensor connected to an Arduino UNO board via the I²C bus to monitor vibration in a machine under test—in this case, a 3D printer. Acceleration data were collected at a frequency of 20 Hz and analyzed using the root mean square (RMS) and the crest factor (cf) to identify differences between normal and abnormal operating conditions.

The results demonstrated that the measurements acquired with the sensor allow for the identification of abnormal operating conditions derived from the detection of vibration anomalies. It was concluded that the MPU6050 sensor is a viable and cost-effective alternative for preventive monitoring and experimental research applications under controlled conditions. However, the sensor's inherent limitations in terms of resolution, dynamic range, and calibration must be considered.

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INTRODUCTION

In the field of academic research and prototype development, accurate vibration measurement is crucial for the analysis and optimization of various mechanical systems. Traditionally, high-end sensors have been the preferred choice due to their accuracy and reliability; however, their high cost limits their accessibility, especially in academic settings and small businesses with limited budgets.

According to Flovik (2018), in the monitoring of machinery and structures using vibration measurements, one of the main areas is the detection of anomalies through the identification of outliers, that is, identifying events or observations that differ significantly from the majority of the data. These outlier vibration data are generally related to some type of problem, such as structural defects, equipment malfunction, etc.

Several recent studies have explored the use of low-cost sensors for vibration analysis in structural and industrial monitoring contexts. Komarizadehasl et al. (2021) developed an inexpensive system based on MEMS accelerometers and Arduino, demonstrating that, through averaging and synchronization strategies, it is possible to achieve accuracy comparable to commercial equipment in the measurement of structural vibrations. In the field of manufacturing, Iqbal et al. (2022) evaluated the performance of low-cost sensors in industrial IoT applications, identifying limitations in the linearity and noise of the devices, but also confirming their viability for monitoring tasks under controlled conditions. Soto-Ocampo et al. (2020) implemented a high-frequency data acquisition system based on low-cost platforms such as Raspberry Pi, aimed at analyzing vibrations in rotating machinery, which demonstrates the applicability of economical solutions in real industrial scenarios.

Currently, sensors such as the MPU6050 have gained popularity for vibration measurement due to their low cost and ability to integrate with development platforms such as Arduino and Python, allowing researchers to perform detailed, real-time analysis and offering a viable alternative to high-end sensors. In addition, the flexibility and scalability of development platforms for integration into measurement systems make them ideal for rapid development and prototyping environments.

Therefore, the central problem of this research is to determine whether the MPU6050 sensor is capable of providing sufficiently accurate and reliable acceleration measurements to detect abnormal operating conditions

abnormal operating conditions in mechanical equipment, which would be of great benefit given the widespread need for accessible and effective vibration monitoring solutions in academic research and prototype development in small businesses.

In relation to the evaluation of measurements, the *root mean square* (RMS) value and the crest factor are used. The RMS value is a descriptive mathematical measure that allows the average magnitude of the signal to be quantified, which in vibration analysis is widely used as an indicator of the overall energy contained in the temporal response of acceleration, velocity, or displacement. Its use is particularly relevant in machinery condition monitoring, as it provides a stable and representative value of vibration severity, reducing the influence of isolated peaks and facilitating comparison with established regulatory thresholds. The crest factor is a widely used indicator in machinery condition monitoring due to its sensitivity to the presence of impulsive phenomena in the vibration signal. Under normal operating conditions, the ratio between the peak value and the RMS value of the signal remains relatively low, reflecting stable behavior without significant irregularities. However, when incipient faults appear in the machinery related to mechanical components, the signal begins to exhibit high-amplitude peaks superimposed on the continuous vibration, causing a notable increase in the crest factor. Consequently, an increase in the crest factor is often associated with abnormal operating conditions, making it a useful tool for early fault detection (Ghazali et al., 2021).

DEVELOPMENT

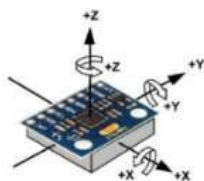
This section provides an overview of the MPU6050 sensor, as well as the instrumentation of the sensors via the I²C bus for collecting vibration data on the test machine—in this case, a filament fusion 3D printer.

MPU6050 Inertial Measurement Unit

Figure 1 shows the MPU6050 sensor, which is an inertial measurement unit (IMU). It is a microelectromechanical system (MEMS) that can be used to measure linear accelerations and angular velocities. The combined use of the integrated 3-axis accelerometer and 3-axis gyroscope allows the movement of a body in three-dimensional space to be determined. It also has an I²C bus interface for writing and reading device registers, operating at a frequency of up to 400 kHz (Fedorov et al., 2025).

The MPU6050 sensor offers several advantages over other inertial sensors; for example, it stands out for its significantly lower cost compared to many high-end sensors, making it accessible for low-budget projects. This sensor combines an accelerometer and a gyroscope on a single chip, simplifying system design and reducing the number of components required. In addition, its ease of use is enhanced by the existence of numerous libraries and code examples available, facilitating its implementation in projects with microcontrollers such as Arduino, ESP32, and Raspberry Pi. Its compact size and light weight make it ideal for applications where space and weight are limited, while its low power consumption is beneficial for portable or battery-powered applications. It uses an I²C interface, which is easy to implement and allows multiple devices to be connected to the same bus. It offers a measurement range suitable for many vibration analysis applications, with adjustable settings for both the accelerometer and gyroscope. In addition, it is a widely available sensor that is easy to purchase on the market. The abundant documentation, tutorials, and online communities provide valuable support for troubleshooting and optimizing the use of the sensor.

Figure 1. MPU6050 inertial measurement unit.

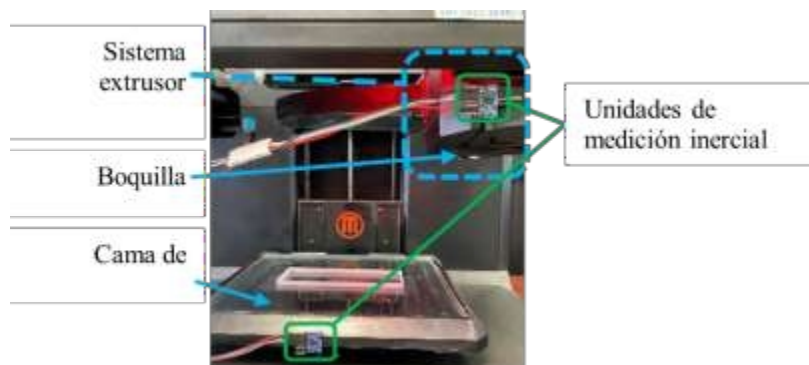


Source: *Internet*.

3D printer instrumentation

Figure 2 shows the instrumentation of the 3D printer (Makerbot Replicator 5th generation) with two MPU6050 sensors, one on the extruder and the other on the print bed. The sensors were connected to an Arduino UNO board via the I²C bus and, once installed in the printer, were calibrated before proceeding with data acquisition.

Figure 2. Instrumentation of the 3D printer.

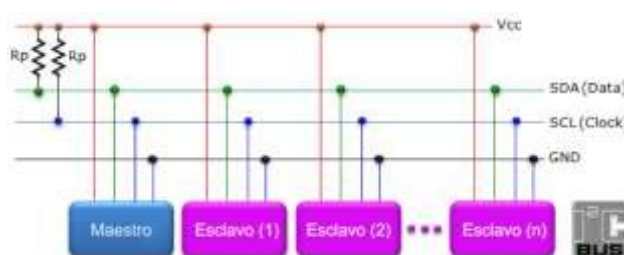


Source: *Own work.*

I²C serial bus

The I²C (Inter Integrated Circuit) serial bus is a master/slave bus with a standard that facilitates communication between microcontrollers, memories, and other devices such as sensors capable of collecting real-world data. Figure 3 shows the structure of the I²C bus²C bus, which handles three connections: SCL (System Clock), the clock pulse line that synchronizes the system; SDA (System Data), the line through which data is transferred between devices; and GND (Ground), common to the interconnection between all devices connected to the bus. The SDA and SCL lines are open drain type, so they must be polarized in a high state by means of pull-up resistors. Additionally, it should be noted that the more data sent over the bus, the greater the saturation of the bus, and therefore it is necessary to calculate the appropriate value of the resistors to ensure uninterrupted communication (*Description and Operation of the I2C Bus, n.d.*).

Figure 3. Structure of the I²C bus.

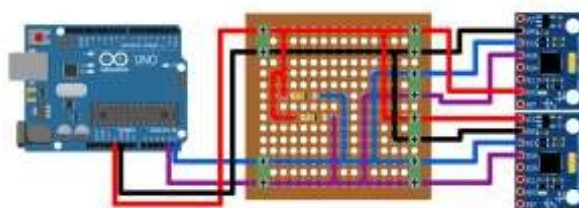


Source: *Internet.*

The MPU6050 sensors act as slaves and are connected to the I²C module of the Arduino UNO microcontroller, which acts as the master, as shown in Figure 4.

It is important to mention that the MPU6050 sensor has integrated pull-up resistors for connecting a single sensor to the serial bus; however, when adding another sensor to the bus, both resistors are insufficient and external resistors must be added. In this case, 10 k Ω resistors were used for both the SCL and SDA lines to connect two MPU6050 devices to the Arduino UNO. However, this does not imply a generalization for any circuit, since in other circuits there may be greater or lesser saturation of the I²C bus depending on the amount of data being shared through the bus.

Figure 4. *I²C bus connection diagram.*



Source: *Images-Internet. Circuit-Esquivel, I.*

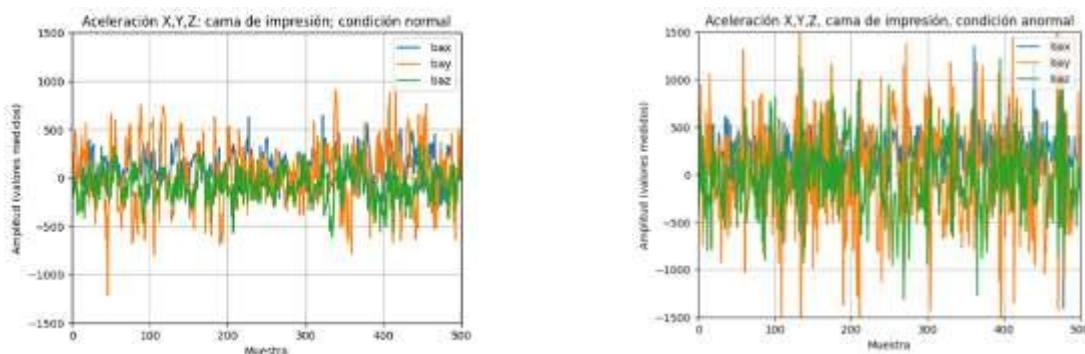
Data collection

Data was collected in CSV format for the X, Y, and Z accelerations of both the print bed and the extruder system at a frequency of 20 Hz. In the specific case of evaluating the sensor in the 3D printer, with an extruder feed rate of 4 mm/s, this means that readings were obtained every 0.2 mm of extruder travel, which the authors considered adequate for detecting vibration anomalies during machine operation for this application.

Figures 5 and 6 show 500 measurements of the amplitude of the signals in the time domain of the X, Y, and Z accelerations of the print bed (identified as *bax*, *bay*, and *baz*, respectively) and the extruder system (identified as *eax*, *eay*, and *eaz*, respectively). In both figures, the graphs on the left show normal operating conditions and those on the right show abnormal operating conditions.

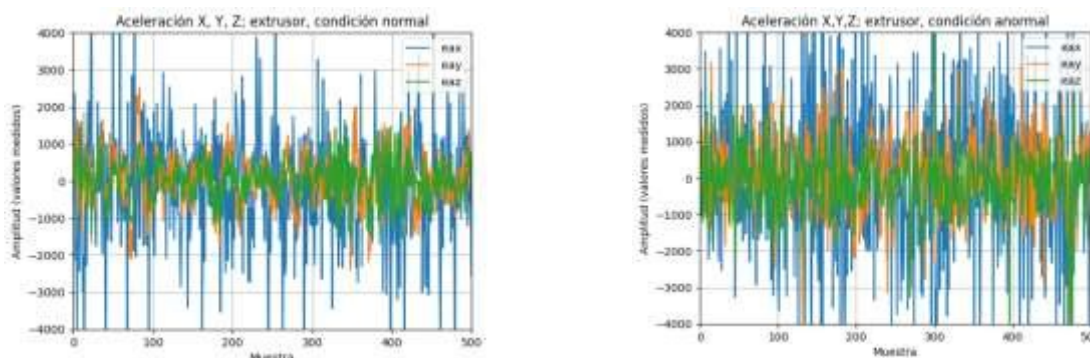
In the case of measurements in the time domain, in the print bed (Figure 5), it can be seen relatively easily that there is a difference in the amplitude of the measured signals. However, in the extruder system (Figure 6), the difference in amplitude is less noticeable.

Figure 5. Acceleration in the time domain of the print bed.



Source: Prepared by the authors.

Figure 6. Acceleration in the time domain of the extruder system.



Source: Prepared by the author.

DISCUSSION AND ANALYSIS OF RESULTS

Analysis with root mean square value.

In order to better appreciate the difference between normal and abnormal operating readings, the root mean square (RMS) value in Figure 7 was applied with a window size of $n=5$.

Figure 7. RMS formula.

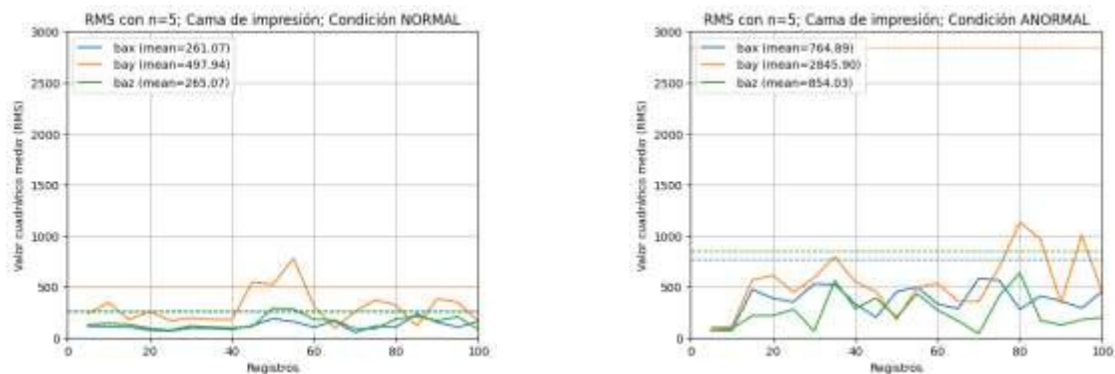
$$RMS(x_{in}) = \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2}$$

Source: Ghazali et al. (2021).

The RMS values are shown in Figure 8 for the print bed and in Figure 9 for the extruder system. Each graph shows the average value for each of the axes (ax , ay , az) with the

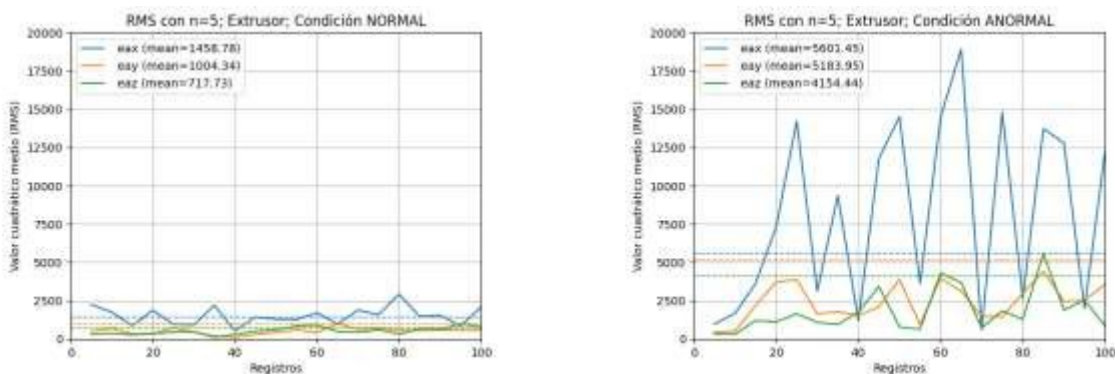
purpose of showing that there is an appreciable difference that allows an upper limit to be defined—for each axis or an average of the three axes—based on normal operating conditions; thus, if a reading exceeds that limit, it would be an indication that the machine has a vibration anomaly.

Figure 8. RMS values; Print bed; Normal vs. Abnormal condition.



Source: Prepared by the author.

Figure 9. RMS values; Extruder; Normal vs. Abnormal condition.



Source: Own elaboration.

Crest factor analysis.

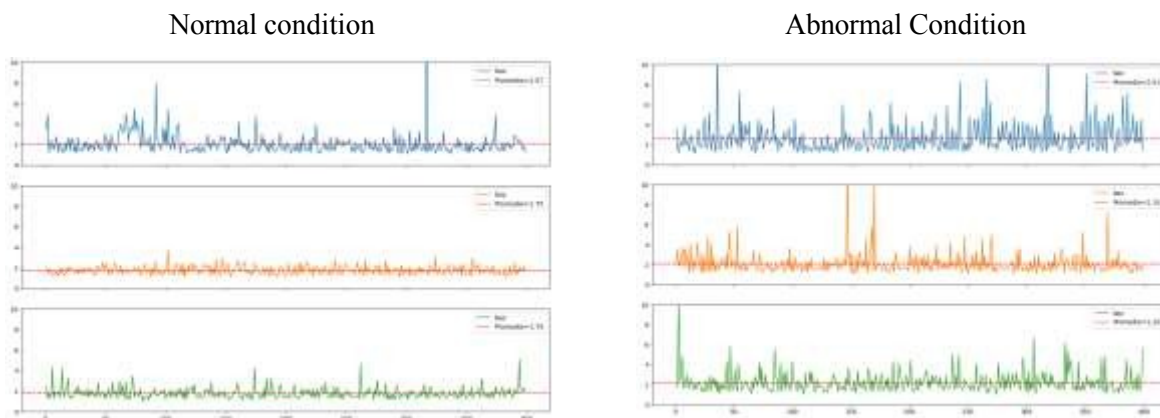
The crest factor (cf) from Figure 10 was applied as a measure of vibration severity with a window size of $n=5$. The crest factor obtained for the printing bed under normal and abnormal operating conditions is shown in Figure 11. It can be seen that for the abnormal condition there is an increase in the average value of cf for the three acceleration variables. For example, *bax* increases from 2.07 to 2.61 under abnormal conditions; *bay* increases from 1.75 to 2.10; and *baz* increases from 1.79 to 2.20, under normal and abnormal conditions, respectively.

Figure 10. Crest factor formula.

$$factordecresta = \frac{valor\ pico}{valor\ RMS}$$

Source: Ghazali et al. (2021).

Figure 11. Crest factor; Printing bed.

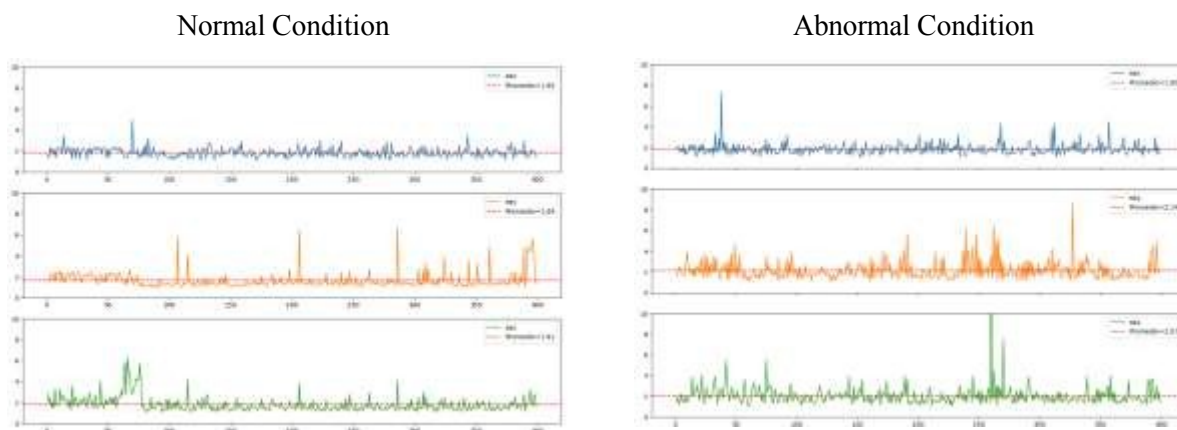


Source: Own elaboration.

Figure 12 shows the cf for the accelerations of the print bed, where it can be seen that for *eax*, *eay*, and *eaz* there is an increase in the average value of the cf.

This is especially true in preventive monitoring and experimental research applications, provided that the inherent limitations of resolution, dynamic range, and calibration are taken into account.

Figure 12. Crest factor; Extruder.



Source: Own elaboration.

The results obtained in this work agree with some relevant aspects reported by Komarizadehasl et al. (2021), Li et al. (2019), and Ghazali et al. (2021) regarding the use of low-cost sensors for the detection of vibration anomalies.

First, it should be noted that even though the differences in the time domain are not very evident—particularly in the extruder system—the analysis with the RMS value allows for a clear distinction between normal and abnormal operating conditions, which is consistent with the findings reported by Komarizadehasl et al. (2021), who mentions that low-cost sensors offer performance comparable to that of commercial systems as long as appropriate processing and calibration procedures are applied.

Secondly, the crest factor showed consistent increases in all three axes under abnormal operating conditions, confirming that the MPU6050 has the ability to record representative vibration peaks that enable early diagnosis of incipient mechanical faults. This is consistent with the findings of Li et al. (2019) and Ghazali et al. (2021), who stated that the crest factor is a sensitive indicator that can detect abnormal vibrations resulting from impulsive phenomena associated with mechanical malfunctions in equipment and machinery. Thirdly, it should be noted that the sensor did not show saturation in any of the channels, which proves that the sampling frequency used (20 Hz) was suitable in this case for measurement in the equipment under analysis. However, in the case of machinery that could exhibit high-frequency vibrations, this would be a point to consider before its application.

From the authors' perspective and based on the results obtained, the MPU6050 sensor is considered appropriate for vibration measurement in both academic research and industry in controlled scenarios, representing a viable alternative to conventional high-end and high-cost equipment.

CONCLUSIONS

This research demonstrated that low-cost MEMS-based sensors such as the MPU6050 inertial sensor are a viable, economical, and scalable solution for vibration analysis in various areas of research in both academic and industrial settings.

The results demonstrate the recording and sampling capacity of the MPU-6050 sensor, showing that the acquisition frequency used is sufficient to accurately represent vibrations in the range of interest. It was also verified that the sensor's operating range is adequate for the conditions evaluated, as no signal saturation phenomena were observed, thus ensuring the reliability of the data obtained.

However, despite its potential, limitations associated with noise, thermal drift, and maximum sampling frequency are recognized, and therefore the implementation of calibration procedures and signal processing techniques is recommended.

FUTURE RESEARCH

The application of frequency domain analysis techniques—Fast Fourier Transform (FFT)—is suggested to perform more comprehensive comparative analyses that allow the performance of the MPU6050 sensor to be compared with industrial accelerometers under the same conditions.

We also suggest the application of machine learning (ML) techniques to generate predictive models evaluating the performance of the MPU6050 sensor in real-time monitoring systems in industrial environments.

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Data curation	Carlos Alberto Ronquillo Salas (70), Ismael Esquivel Mancha (30)
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Writing - Review and editing	Carlos Alberto Ronquillo Salas (60), Laura Elizabeth Silva Leyva (20), Irving Bruno López Santos (20)