Electronic Unit for the Management of Energy Harvesting of Different Piezo Generators

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Abstract: The constant advance in the development of piezoelectric materials for energy harvesting has demanded new implementations in the electronics field. The piezoelectric property of these materials has been considered an energy source for low-power devices; nevertheless, the units that provide energy are usually adapted to just one piezoelectric device. This aspect complicates the process, taking into account the amount of time needed for an energy harvest; therefore, this research inquired at first into the adequate piezoelectric materials for carrying out the current study. Afterwards, an energy management unit was designed, considering the connection between some modules and allowing the sourcing of an electrolytic cell for producing hydrogen and, in turn, energy. The results evidence a decrease in time charging of the energy storage unit, which allows a cell’s supply of energy in shorter time intervals, its design efficiency being about 90%, in such a way that the energy harvested through the piezoelectric devices can be used in a better manner.

Keywords: piezoelectric device; converter; buck; boost; electrolysis; frequency; voltage

1. Introduction

The piezoelectric devices as energy harvesters are founded on the physical principle of one-way functions; this parameter assumes the voltage polarity when it is subjected to a mechanical pressure as material compression or bending [1]. However, not all the piezoelectric devices can be categorized as energy harvesters due to the constants of electromechanical connection, which should be high for increasing the conversion rate between mechanical and electrical energy [1]. By means of these constants and depending on the material type and form, the viability of the piezoelectric device is determined as a low-power energy source.

Nowadays, the advances in the field of harvester materials have been focused on kinetic energy harvest, produced through applications as bicycles vibrations [2], the energy produced by the air currents [3–5], or the energy applied with the compression of a piezoelectric device [6]. Even though there are diverse applications of piezoelectric elements in the renewable energy domain, there is still a difference between the power provided by the material and the necessary power to the functioning of an electrical device [7]. On one hand, this problem consists in the time needed by the piezoelectric device for harvest the necessary energy to energize the device; on the other hand, it consists in the energy storage unit, as it is commonly adapted to only one piezoelectric module. In consequence, these situations complicate the transition between the energy harvester materials and the alternative energy sources.

Usually, the energy harvester materials have an energy management unit based on a rectifier that converts alternating current to direct current, that is to say, a buck or boost...
converter that regulates the output voltage, followed finally by a stage of storing energy [8]. This approach allows the design of an electrical circuit able to connect the piezoelectric impedances and the energy storing module in such a way that there is a greater efficiency, which in turn determines the piezoelectric impedance when its resonance frequency is disturbed, finally obtaining the maximum energy from the material. Even so, it is a well-known fact that the power of the piezoelectric material is about a few milliwatts; that is to say, for a device of around five milliwatts, the time between obtaining the energy and energizing the device will be very long. For that reason, it is necessary to work on a design able to connect diverse modules to optimize the energy management unit in such a way that electrical devices can be powered in an efficient way and in a timely manner.

This article and study will establish the piezoelectric elements that are appropriate to energy applications, evaluating the physical properties of the material, its form, and its frequency resonance. Subsequently, the study will determine the adequate mechanical stress to obtain a higher conversion rate, and a circuit will be designed; this will help the obtaining of the maximum energy from the piezoelectric device so that in the design of the energy management unit, it will be possible to connect diverse circuits while decreasing the time charging. Finally, with a power rating of four watts, an electrolytic cell will be powered for producing hydrogen in order to determine, in turn, the viability of the electronic design by evaluating the efficiency and the time passed between the charging and discharging of the energy storage element.

2. Materials and Forms of the Piezoelectric Elements

Piezoelectric devices as energy generators can be ceramic, which are characterized by having high electromechanical connections constants, which also makes energy conversion high. Even so, as it is a rigid material, its implementation is limited to the applied force; that is to say, the compression of a material depends on its strain rate to avoid its break. One of the ceramic materials is PZT (4, 5A, 5H, and 8), whose connection constants are between 0.6 and 0.7, such as PMN-33 and PZN-6, whose connection constants are 0.9 [6].

Additionally, another kind of piezoelectric material is the polymer, which is characterized by having lower electromechanical connections constants than the ceramic one and a higher strain rate. Nevertheless, this is not a common material in applications that imply the transformation of mechanical energy into electrical energy, taking into account that its electromechanical conversion is reduced as a consequence of the electricity that it generates after being compressed. As a result, the polymer-based piezoelectric devices focus on the use of applications as actuators, which are characterized by converting an electrical signal into a mechanical one; this generates the maximum strain on the material and allows its use in applications such as robotics, medicine, and information technology, among others. An example of these kinds of piezoelectric devices can be PVDF and BaTiO₃.

The piezoelectric forms play an important role in energy production, considering parameters such as the force distribution, which can change the behavior of materials, since as these are compressed, the force applied on their surface is not uniform [1]. Moreover, there are parameters such as the resonance frequency, which indicates the frequency at which the material can generate the maximum energy; there are also electrical parameters that define the current in a short circuit and the voltage in an open one, in Figure 1 shows the circuit of the previous topologies. Voltage in an open circuit refers to the strain of the material without producing any flow of electrons from an electrode to the other when the current is zero. Additionally, the term current in short circuit describes the moment in which the material is strained and the electrons are able to pass the electrodes, that is to say, when the voltage is zero and there is a maximum current. However, it is necessary to recognize the maximum current of the piezoelectric device, taking into account that demanding an amount of energy over the capacity of the material could break it down. That is the reason why the piezoelectric device should be evaluated on its voltage and current in order to find an optimal point for its operation [9]. In Figure 2, a graph of the optimum operating point is shown.
In Equations (2) and (3), there are two manners of representing voltage; the first one is related to the applied force, and the second one is related to the distance of material compression, demanding an amount of energy over the capacity of the material could break it down. That is the reason why the piezoelectric device should be evaluated on its voltage and current. 

Regarding the calculation of the resonance frequency, there are detailed mathematical models that relate the applied force with respect to the physical variables of the material; however, the most important ones are the circular and the rectangular forms (Figure 3). In rectangular forms, the reference point is commonly located at one of the sides, which limits the movement in the vertical axis as the force is applied. For that reason, the energy is generated through material bending, contrary to the circular forms, in which material compression generates electrical energy.

The voltage vs. the current of a piezoelectric material in which Op represents the operating point of maximum work and Dv refers to the direction of the increased voltage [11]. Considering the parameters mentioned before, there are diverse forms for generating electrical energy; however, the most important ones are the circular and the rectangular ones (Figure 3). In rectangular forms, the reference point is commonly located at one of the sides, which limits the movement in the vertical axis as the force is applied. For that reason, the energy is generated through material bending, contrary to the circular forms, in which material compression generates electrical energy.

Figure 1. Topologies of a piezoelectric transducer in which Cp and Rp represent the capacitance and the resistance of the piezoelectric device (a) as a charge generator and (b) as a voltage generator [10].

Figure 2. The voltage vs. the current of a piezoelectric material in which Op represents the operating point of maximum work and Dv refers to the direction of the increased voltage [11].

Figure 3. Recurring topologies for energy harvesters. (a) Rectangular form; (b) circular form [11].

Regarding the calculation of the resonance frequency, there are detailed mathematical models that relate the applied force with respect to the physical variables of the material;
these can be found in articles [10–16]; even so, the simplified variables are shown below. The following equations correspond to the rectangular form:

\[
F_r = \frac{16T}{L^2} \sqrt{\frac{Y_{11}}{p}} \tag{1}
\]

\[
V = \frac{3L^2}{2WT} g_{31} F \tag{2}
\]

\[
V = \frac{3T^2}{8L^2} Y g_{31} \Delta X \tag{3}
\]

\[
I = \frac{3L^2}{2L^2} d_{31} F \tag{4}
\]

\[
I = \frac{3TW}{8L} Y d_{31} \Delta X \tag{5}
\]

In Equations (2) and (3), there are two manners of representing voltage; the first one is related to the applied force, and the second one is related to the distance of material bending, and the same goes for the representation of current equations; it should be pointed out that \(d_{31}\) refers to the displacement coefficient, \(g_{31}\) refers to the voltage coefficient, and \(Y_{11}\) to Young’s modulus.

The following are the equations for the circular form, considering that there are two manners of representing for voltage and current.

\[
F_r = \frac{T}{D^2} \sqrt{\frac{Y_{11}}{p}} \tag{6}
\]

\[
V = \frac{56}{T} g_{31} F \tag{7}
\]

\[
V = \frac{4.1T^2}{2D^2} Y g_{31} \Delta X \tag{8}
\]

\[
I = \frac{0.42D^2}{T^2} d_{31} F \tag{9}
\]

\[
I = \frac{3.1T}{T} Y d_{31} \Delta X \tag{10}
\]

3. Types of Mechanical Stress

The use of energy harvesting materials such as piezoelectric devices transforms a mechanical stress into an electrical one; nonetheless, in the energy conversion, it is important to take into account that the efficiency of these piezoelectric devices is very low; that is to say, the energy obtained by the applied force is not equivalent, rather drastically reduced. Therefore, the study of the forces involved in the transformation of energy is essential to not waste the mechanical energy; in other words, this study allows the recognition of the amount of energy by analyzing what the kind of force that obtains the highest conversion rate when compressing or disturbing the material is, avoiding the application of disproportionate force.

In the course of this research [17], different articles were studied; these illustrate diverse methods of energy harvesting through piezoelectric materials, such as the following topologies.

According to Figure 4a, the material presents a high strain to the degree of being in the limits of bending; also, as it concentrates the stress force in one direction, a nonlinearity is created in the system as a consequence of the movement, limiting the natural response of the material. On the basis of these results and adding the nonlinearity characteristic, there is an increase of about 50% on the piezoelectric power. Additionally, the second topology refers to putting a mechanical charge that bends the material, as it is shown in Figure 4b,
in which the deformation limits depend on the external force. In this case, deforming the material with this kind of disturbance improves the energy transfer so that the electrical output power increases in comparison to the previous topology.

Figure 4. Types of mechanical stress for a rectangular piezoelectric device: (a) mechanical stress; (b) mechanical charge; (c) magnetic force.

The last topology focused on deforming the system while taking into account that the material has an only reference point, as is evidenced in Figure 4c; starting from that point, the piezoelectric disturbance was given by magnetic fields; that is to say, a magnet was put in the right side of the material for generating oscillations in the system through magnetic fields. As a result of this test, the bandwidth covered about 100%, which means that it was possible to disturb the system so that the movement carried out was in the same resonance frequency of the material, and then the generated voltage increased, and therefore, the efficiency of this model was better than the one of previous topologies.

4. Stages of the Energy Harvester Module

A design of the energy source that allows energy harvest through a mechanical stress is as important as choosing the piezoelectric device, considering that this allows us to transfer the obtained energy to a battery or to a different harvest form. That is why the general diagram for the energy harvester module is composed by three parts [18]: the signal conditioning stage, the energy transfer stage, and the storage stage.

One of the main obstacles for harvesting energy from non-conventional sources such as piezoelectric energy is the design of a circuit that allows energy transformation while keeping high efficiency. Therefore, given that because of their physic properties the piezoelectric materials expand and contract, their strain results on the alternating current, which should be conditioned to the form of a direct wave for the storage process.

In terms of the signal conditioning, there are manners to rectify or convert alternating signal to direct signal; this is done through semiconductor elements such as diodes, which behave as a one-way switch [19]; that is to say, they only allow the passage of energy from the positive semi-cycle and put the negative one aside. As a consequence, there are different configurations that allow the signal rectification by means of these components; however, it is necessary to know the efficiency of those configurations, taking into account that working with low-power energy sources makes it necessary to minimize the circuit losses. A full-wave rectifier is showed below (Figure 5), and even if its efficiency is about 98%, working with low currents makes it essential that diodes be specialized in rectifying low-power signals.

Based on the previous circuit and in order to get the minimum ripple, the capacitor is calculated, considering that the higher the capacitor or resistance are, the longer the capacitor will take to charge. Moreover, the resistance is selected according to the charge resistance supported by the piezoelectric. To do that, it is required to analyze the piezoelectric according to Section 2.
The seventh equation defines the capacitor depending on the ripple wanted; there, $F$ refers to the frequency at which the piezoelectric is disturbed, $F_R$ refers to the ripple’s factor percentage wanted, $R$ refers to the charge resistance, and $Q$ to the number of signal pulses per period.

\[
C = \frac{\left(\frac{1}{\sqrt{2}F_R}\right) + 1}{2QF \cdot R} \tag{11}
\]

The operating mode of a buck converter is affected when the switch (Mosfet Q1) is activated and deactivated. For that reason, the passive components respond differently according to the time; differential equations are also affected.

The currents and voltages of passive components are determined from the operation modes, with the objective of finding the transfer equation and the values in steady state.

For the operation mode of Figure 7a, the differential equations are the following:

\[
\frac{d_i L}{d_t} = -\frac{V_C}{L} + \frac{V_{in}}{L} \tag{12}
\]
For the operation mode of Figure 7b, the differential equations are the following:

\[
\frac{di_L}{dt} = -\frac{V_c}{L} \tag{14}
\]

\[
\frac{dv_C}{dt} = \frac{i_L}{C} - \frac{V_c}{R \cdot C} \tag{15}
\]

It is important to mention that for implementing this converter, there should be a controller to increase or decrease the power cycle of the PWM signal, considering that it is necessary to regulate the output voltage. Otherwise, it is essential to clarify that the driver that activates the mosfet Q1 should have a different reference (GND) to the output voltage; isolated drivers with independent sources are usually used for that.

For this last stage, it is possible to use a battery for the storage; nevertheless, and given the low current of the piezoelectric device, the charging circuit would not be able to charge the battery optimally. To solve this problem, it would be possible to use super capacitors, which are a simple but expensive option because of the quantity of capacitors needed with a high capacitance able also to energize the electronic devices.

5. Design

Based on the stages of Section 5, the rectifier and converter were implemented. Even as the current of the piezoelectric was very low, it was harder to design a converter, because its efficiency was very low too. For those reasons, the circuit of Figure 8 was implemented; it replaces the signal conditioning stage and the energy transfer stage; it is a specialized circuit for low power applications. Moreover, this circuit is focused on harvesting piezoelectric or solar panel signals in a cell in such a way that its efficiency is high compared with developing the stages separately.

In regards to the diagram represented by Figure 8, it is important to mention that there are some conditions to source an electrolytic cell or another low-power device; one of these is the LTC-3588 maximum output current, considering that its low current makes impossible to power the device. In consequence, the following diagram is proposed (Figure 9). There, the energy harvester module (LTC-3588) sources a super capacitor bank for energizing the electronic device with these.
5. Design

Based on the stages of Section 5, the rectifier and converter were implemented. Even though the stages were developed separately, the circuit was proposed as one, in consequence of resistance $R_1$ and $R_2$, which is zero ohm. Finally, when selecting the output voltage, it is necessary to connect pins $D_0$ and $D_1$ to $gnd$ or $V_{in2}$; in this case, the voltage selected was of about 3.6 V; as a consequence, the pins should be connected to $V_{in2}$.

During the storage stage, it was conditioned to the energy management unit, as it is necessary to transfer the super capacitors’ energy as these are charged; the design proposed meets these requirements.

The diagram in Figure 10 shows a relay ($U_3$), which is responsible for supplying the energy of the super capacitors when these are charged at their maximum voltage. Moreover, on the left side are the connectors that connect the ten energy harvesting modules to charge the super capacitors faster.

Figure 8. Integrated circuit LTC-3588.

Figure 9. Diagram used for the development of the energy harvester module.
The microcontroller (Figure 11) detects the voltage of the capacitors to control the switching on of the relay, on the other hand, the regulators of Figure 12 are in charge of feeding the microcontroller (Figure 12a) and regulating the voltage of the capacitors (Figure 12b). In regard to the converters, these are designed to regulate a voltage of 5 V; additionally, to optimize the energy of the management unit, it is necessary to select a relay and a microcontroller that use little energy in order to ensure that the battery will power the relay and that the controller will not run flat rapidly. It is important to specify that the battery that powers the components mentioned before does not affect the charge of the capacitors.

Figure 10. Diagram of the energy storage circuit with its respective relays.

Figure 11. Microcontroller connections to control charging and discharging of capacitors.

Figure 12. Boost converters: (a) to source the microcontroller and the relay; (b) to regulate the output voltage of the super capacitors.
6. Results

The results are divided into two parts: the first one is related to determining the time of charge of the capacitors to develop the tests in the energy management module. The second one consists in energizing an electronic device by developing tests of the device for determining the viability of the design proposed.

6.1. Capacitor Charging

At the beginning, the charging time of some capacitors was determined according to the energy harvested by a piezoelectric (Table 1) and aiming at evidencing the relationship between the voltage and the current in an energy storage component. Regarding the charging voltage, it was 3.5 V, which corresponds to the output voltage of the module developed from Figure 9, and its maximum current was 500 μA.

Table 1. Charging time of the capacitors.

| Capacitor | Time (s) |
|-----------|----------|
| 100 μF    | 3.5      |
| 1000 μF   | 22.5     |
| 4700 μF   | 95.2     |
| 9.4 mF    | 252      |

The way to collect piezoelectric energy is similar to the showed in Figure 4c, due to the fact that there is only one reference point, and the material movement is vertical; it is important to mention that the movement occurs from the vibrations produced by a flexible support, which oscillates while applying a momentary force and as a consequence causes the material bending and production of energy. In Figure 13 shows the device that collects energy.

In relation to the charge of the super capacitors of the energy storage unit (Figure 10), the equivalent capacitor is 10 F; therefore, both the storage time and the stored energy will be higher. This energy increase causes the LTC 3588 module to not transfer 3.5 V but a lower voltage, even if it was configured for a higher one. This problem is caused by the super capacitor’s impedance, for which the energy harvester module decreases the voltage, as it cannot change the capacitor capacitance from the formula of the energy stored in a capacitor. Table 2 shows the capacitor charging time equivalent to 10 F.

Figure 14 shows the connection of two energy harvesting modules to the energy management card and to a battery of 3.7 V that sources the microcontroller and the relay. Even if in Figure 12a, the input voltage refers to 1.8 V, it is possible to source the converter from 0.7 to 5 V in such a way that the output voltage be regulated to 5 V. Moreover, the
second connector corresponds to the super capacitors’ energy voltage, also regulated by the scheme in Figure 12b, which transfers 5 V so that it is possible to regulate this voltage with an external converter that allows the energizing of the low-power device with the voltage wanted.

Table 2. 10 F Super capacitor charging time with a piezoelectric device.

| Voltage (V) | Time (s) | Time (m) |
|------------|----------|----------|
| 0.5 V      | 5636     | 93       |
| 1 V        | 17,548   | 292      |
| 1.4 V      | 32,320   | 538      |
| 1.8 V      | 66,736   | 1112     |

Figure 14. Way of connecting two energy harvesting modules to the energy management card.

In the same way as the waveform of the charge of the energy management module capacitors was found from Figure 15, the time of charge was determined with two energy harvesting elements.

Figure 15. Waveforms of the charge time of the 10 F super capacitor with only one piezoelectric device.

Comparing Figures 15 and 16 illustrates the relationship in which the greater the number of energy harvesting components, the shorter the charging time of the super
capacitors (Table 3). Moreover, it was evidenced that the charge time was reduced by about half as a consequence of the fact that each piezoelectric device is able to supply a maximum current of 500 µA; thus, as there were two energy harvesters, the maximum charge current tended to 1 mA. Based on this information, it is possible to determine the charge time when having ten modules; this can be carried out with help of a voltage source current limited to 5 mA. In Figure 17 shows the emulation with a voltage source.

Table 3. 10 F super capacitor charge time with two piezoelectric devices.

| Voltage (V) | Time (s) | Time (m) |
|------------|----------|----------|
| 0.5 V      | 4513     | 75       |
| 1 V        | 10,549   | 175      |
| 1.4 V      | 18,166   | 302      |
| 1.8 V      | 36,945   | 615      |

Figure 16. Waveforms of the charge time of the 10 F super capacitor with two piezoelectric devices.

Figure 17. Emulation of the capacitors’ charge with a current-limited voltage source.
6.2. Energize the Device

Based on the data gathered from the charging time of the capacitors, the low-power electronic device was energized, which in this case will be an electrolytic cell for producing hydrogen (Figure 18). Nevertheless, it is necessary to characterize the cell with respect to the current and voltage consumption for determining the optimal operational voltage in relation to the energy harvested. Moreover, the tests were developed based on the time spent by the cell producing 20 mL of hydrogen. Table 4 shows the characterization of the electrolytic cell.

![Figure 18. Mounting of the hydrogen cell (transparent) and a fuel cell (blue).](image)

**Table 4.** Characterization of an electrolytic cell in terms of voltage and current.

| Voltage (V) | Current (A) | Time (s) |
|------------|-------------|----------|
| 1.6 V      | 0.18 A      | 364      |
| 1.7 V      | 0.46 A      | 150      |
| 1.8 V      | 0.76 A      | 105      |
| 1.9 V      | 1.12 A      | 66       |
| 2 V        | 1.46 A      | 56       |
| 2.1 V      | 1.76 A      | 43       |
| 2.2 V      | 2.08 A      | 37       |
| 2.3 V      | 2.58 A      | 32       |

According to the previous chart, it is possible to choose the value corresponding to the application that you want to implement, which in this case was 1.8 V considering that both the current consumption and the time for producing 20 mL of hydrogen are not that high.

In terms of selection of the cell operating voltage, if the consumption current is not taken into account, it is very probable that the cell’s efficiency is under 30%, which is related to the losses suffered by the cell when working with very high currents.

For energizing the cell with a voltage of 1.8 V, a buck–boost converter (LM 2577) was connected to the management module output, taking into account that this converter keeps the output voltage unchangeable independent of the input voltage value. It is also essential to mention that now the maximum voltage transferred by the energy management module is 2 V; however, as the boost converter in Figure 12b works with a minimum voltage of 0.7 V, the output value will be 5 V, approximately.

The tests carried out revealed that for each charge of the super capacitors, the cell is able to produce approximately 3 mL of hydrogen with an average current of 800 mA, so that the power supplied is about 1.5 watts in a time interval of 5 to 10 s.
7. Discussion

According to the results, it is possible to affirm that it is viable to source a low-power electronic device provided that there are more than 10 energy harvesting modules and considering that the capacitors’ charging time is very long when there are less than 10 piezoelectric devices, which would not justify the time spent on the harvest. However, it is possible to source an electronic device that consumes less than 100 mA by harvesting energy from one or more piezoelectric devices. Regarding the capacitors’ energy, it is recommended to use capacitors with higher capacitance for energizing devices with rated power of about 5 to 10 watts; in this way, they could transfer more energy. Nonetheless, it is necessary to emphasize the fact that the charging time will be increased, and the output voltage of the harvester module will have a maximum voltage of 2 V; that is the reason why it is essential to design a circuit of the management unit, considering that the output voltage of the LTC 3588 circuit is not going to be 3.5 V.

With respect to the capacitors’ charge, it was done from a constant voltage source, but as it is known, as the capacitor is being charged, the current tends to decrease until zero amperes, and for that reason, the last part of the charging process tends to take a very long time, considering also that the current is very low. Taking this into account, for future studies, it is suggested to charge the capacitors with a constant current source; in this way, the waveform is not going to be exponential, but it is going to be a straight line whose slope will be directly related to the current that it supplies. The current source is a challenge, as working with such low currents demands carefully selecting the electronic components, and, moreover, electronics become complicated; the development of the source mentioned before would implicate a drastic decrease in the charging time, and as a consequence, it would optimize the capacitors’ charging.

8. Conclusions

Some energy harvesting modules were implemented with the objective of decreasing the charging time of an energy storage element. The results show that the charging time is long when one piezoelectric device is used; nevertheless, when using more piezoelectric devices, this amount of time decreases in such a way that it is possible to energize electronic devices that do not use very high currents, which represents a very interesting low-power alternative source for energy applications. According to the design of the energy harvesting modules, the output diode should have a low direct voltage for the capacitors’ charge to achieve a higher voltage and to harvest more piezoelectric energy. The connection of the impedances of the energy harvester module to the super capacitor results in a voltage drop because of the super capacitor electric model; moreover, as the piezoelectric device provides such a low current, the harvester module is not able to regulate the output voltage wanted.

The use of rectangular forms in piezoelectric materials provides different options to develop piezoelectric energy harvesters in such a way that the topology in which there is only a reference point and whose movement is vertical results in a high conversion of mechanical energy to electrical, which also provides more energy from the same mechanical stress.

Finally, in terms of energizing an electrolytic cell or another electronic device, the management module should be able to provide the necessary current to achieve an optimal functioning when energizing the device; in consequence, it is necessary to select the electronic components so that the efficiency of the component is high and its maximum functioning current is higher than the current that is expected to be provided.

Author Contributions: Conceptualization, E.F.-G., M.J.T., and J.R.-P.; software, S.R.-M.; validation, E.F.-G., M.J.T., and J.R.-P.; investigation, S.R.-M. and E.F.-G.; writing—original draft preparation, S.R.-M. and E.F.-G.; writing—review and editing, E.F.-G.; supervision, E.F.-G., M.J.T., and J.R.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.
**Informed Consent Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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