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## PROTOTYPE DESIGN FOR AUTOMATED DOSING USING ARDUINO AND FERTILIZER LOAD MONITORING FOR AGRICULTURAL COMPANIES IN SINALOA

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DOI: <https://doi.org/10.61273/neyart.v4i1.173>

Received: 12/20/2025 | Accepted: 02/27/2026 | Published: 04/01/2026

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**Abstract--** In northern Sinaloa, the loading of granular fertilizers is still carried out manually or with limited mechanization, leading to operational inefficiencies, safety risks, and variations in dosing. This article presents the design and implementation of a prototype automated *dosing machine*, a stationary dosing and loading system controlled by an Arduino microcontroller and monitored via a mobile app. The objective is to improve operational efficiency, dosing accuracy, and personnel safety in agricultural companies in the region. The methodology includes an analysis of the traditional process, the design of an architecture featuring a hopper, a gravimetric dosing unit with load cells, Arduino-controlled actuators, and a remote monitoring interface, as well as the simulation of loading times. Theoretical results show reductions of 25–40% in loading time, accuracies close to  $\pm 1\%$ , and reduced staff exposure to dust and physical exertion. Finally, adoption barriers and benefits in productivity, ergonomics, and traceability are discussed.

**Keywords—**Application, Arduino, Agricultural automation, Fertilizer dosing, Monitoring, Occupational safety.

**Abstract --** In northern Sinaloa, granular fertilizers are still loaded manually or with limited mechanization, leading to operational inefficiencies, safety risks, and variations in dosing. This article presents the design and implementation of a prototype automated dispenser, a stationary dosing and loading system controlled by an Arduino microcontroller and monitored via a mobile application. The objective is to improve operational efficiency, dosing accuracy, and personnel safety in agricultural companies in the region. The methodology includes an analysis of the traditional process, the design of an architecture featuring a hopper, a gravimetric dispenser with load cells, Arduino-controlled actuators, and a remote monitoring interface, as well as the simulation of loading times. Theoretical results show reductions of 25–40% in loading time, accuracies close to  $\pm 1\%$ , and lower exposure of personnel to dust and physical strain. Finally, adoption barriers and benefits in

productivity, ergonomics, and traceability are discussed.

**Keywords:** Agricultural, application, Arduino, automation, fertilizer dosing, monitoring, occupational safety.

## INTRODUCTION

The northern region of Sinaloa, strategically located thanks to the connectivity of the port of Topolobampo, is distinguished by its high agricultural productivity and the use of advanced technologies in crops such as corn, wheat, and vegetables (INEGI, 2024). Despite the degree of mechanization achieved in various stages of the agricultural process, manual practices persist in the handling of solid fertilizers, particularly in transferring them to seeders, spreaders, and fertigation equipment. These practices, based on handling 50-kg bags, create operational bottlenecks and affect staff efficiency and safety, in addition to introducing variations in the applied dose, generally estimated empirically with errors of  $\pm 5\text{--}8\%$  (CIMMYT, 2025).

In contrast, industrial and agro-industrial sectors have widely adopted automated systems for dosing and material handling, which have demonstrated significant improvements in efficiency, precision, and traceability (Universal Robots, n.d.). Automation using gravimetric systems allows for errors of approximately  $\pm 1\%$ , facilitating uniform nutrient application and reducing waste (Ortiz Henao et al., 2010). However, its adoption in the regional agroindustry remains limited due to economic, cultural, and technological infrastructure barriers (López et al., 2023).

In this context, the central question arises: To what extent can the implementation of an automated dispenser improve efficiency, precision, safety, and time optimization in fertilizer loading activities at agricultural enterprises in northern Sinaloa? To answer this, this study proposes the design of a prototype based on an Arduino microcontroller and controlled via a mobile app, evaluating its technical feasibility and potential benefits.

## DEVELOPMENT

### Theoretical Framework

The development of an automated dispenser requires an understanding of the fundamentals of fertilizer dosing, automation applied to agricultural processes, and the regional conditions that influence its operation.

#### a) Fertilizer Handling and Dosing

Agricultural dosing is performed using volumetric or gravimetric methods. The former regulate the amount based on valve opening time or mechanical adjustments; although they are simple and low-cost, they are highly sensitive to the bulk density, moisture content, and flowability of the material (CIMMYT, 2025). The latter use load cells to weigh the fertilizer directly, achieving accuracies of  $\pm 1\text{--}2\%$  and

enabling data logging, which is why they are preferred in precision agriculture (Ortiz Henao et al., 2010; XJCSENSOR, 2023). Correct dosing is essential for optimizing nutrient use and minimizing environmental impacts; studies show that proper calibration reduces overdosing by more than 5% and that microcontroller-based systems can achieve accuracies close to  $\pm 1\%$  (Ortiz Henao et al., 2010). This highlights the need for automated technologies that ensure uniformity and accuracy in the field.

The importance of improving precision is supported by the fact that up to 40% of the nitrogen applied to intensive crops can be lost due to inefficient management practices, affecting productivity and increasing the cost per hectare (Fageria, 2016).

#### b) Industrial automation applied to agriculture

Agricultural automation integrates electronic, pneumatic, and computerized technologies to perform repetitive tasks with high precision. An automated dosing system incorporates microcontrollers such as Arduino or ESP32, weight and level sensors, HMI interfaces, and IoT connectivity for remote monitoring, as well as reliable actuators to drive augers, gates, or belts (López et al., 2023; Rivera-Méndez et al., 2021). Although adoption in the agricultural sector has been slower than in industry, its use in stationary operations is technically feasible and improves safety by reducing manual handling of loads. In Mexico, NOM-006-STPS-2014 requires minimizing the manual handling of heavy materials and using auxiliary equipment to reduce ergonomic risks and exposure to hazardous agents (STPS, 2014), reinforcing the relevance of systems such as automated dosing machines to comply with regulations and professionalize operations.

#### c) Regional conditions in northern Sinaloa

The system design takes into account the region's specific characteristics: high seasonality in agricultural demand (CONAGUA, 2023); extreme weather conditions (high temperatures, radiation, dust, and humidity) have been documented; and corrosive materials such as hygroscopic fertilizers, which require epoxy coatings, stainless steel, and electrical protection with IP65 enclosures to extend the equipment's service life (SADER, 2024). Variations in staff training necessitate an intuitive interface in Spanish and robust industrial controls, accompanied by ongoing training. The diversity of production scales demands scalable solutions, ranging from high-capacity stationary systems

capacity to mobile or semi-mobile versions for shared use. Additionally, cooperative financing schemes can be implemented to facilitate their adoption.

Taken together, the technical, climatic, and socioeconomic conditions in northern Sinaloa create a favorable environment for implementing automated fertilizer management systems (INEGI, 2024). Despite the challenges associated with climate, training, and crop diversity, the region possesses the necessary infrastructure and technological interest to ensure the operational viability of the automated dispenser, laying the groundwork for the design and evaluation presented in the methodology.

#### d) **Arduino Technology**

Arduino technology represents an open-source hardware and software platform widely used in the development of embedded systems and automation prototypes. Its architecture, based on AVR, ARM, or ESP32 microcontrollers, together with an accessible programming environment, allows for the implementation of control algorithms, data acquisition, and serial communication with high efficiency and low cost (Banzi & Shiloh, 2022). Arduino stands out for its versatility in integrating sensors and actuators via digital, analog, and PWM pins, as well as supporting communication protocols such as I2C, SPI, and UART. Its ecosystem of libraries and expansion boards facilitates the modular design of systems focused on measurement, control, and wireless connectivity (Monk, 2019; Margolis, 2020).

#### e) **Application Software**

Application software consists of programs designed to perform specific user-oriented functions or specialized processes within a computer system. Unlike system software, which is intended to manage hardware resources, application software facilitates activities such as data processing, monitoring, control, and analysis in automated systems (Sommerville, 2016). Its architecture may be based on client-server models.

In agricultural automation, application software is crucial for enabling interaction between the user and physical control systems. Mobile applications, web interfaces, and IoT platforms allow for monitoring operational variables, managing dosing, storing records, and visualizing parameters in real time. These tools increase precision, traceability, and efficiency in tasks such as fertilization, irrigation, and agricultural logistics (Wolfert et al., 2017; Liakos et al., 2018). Integrated with microcontrollers or PLCs, application software enables remote operations, diagnostics, and

data-driven decisions, enhancing automation and process safety (Nguyen et al., 2020).

#### f) **Automated Systems**

Automated systems are sets of devices, sensors, controllers, and software designed to perform tasks with minimal human intervention. These systems integrate mechanical, electrical, electronic, and computational components to carry out operations precisely, repeatably, and efficiently. Automation helps reduce variability, improve operational times, and increase safety, especially in industrial and agro-industrial environments (Groover, 2020).

#### **Methodology**

This study is applied and feasibility-based, combining field research with the development of a functional prototype. The methodology followed several complementary stages. First, a requirements analysis was conducted through interviews with field supervisors and machinery managers to characterize current fertilizer management practices: most commonly used types (urea, DAP/MAP, ammonium sulfate, NPK blends), common forms (50-kg bags and bulk), typical volumes per load (200–1,500 kg), and receiving equipment such as spreaders, truck hoppers, and big bags.

Subsequently, an analysis of the current process was conducted, recording manual and semi-mechanized loading times. It was found that 2–3 people take between 10 and 15 minutes to unload 1 ton, in addition to facing multiple operational risks (repetitive lifting, falls, exposure to dust). These data established the baseline for quantifying the potential benefits of automation.

Using this information, a conceptual design for the automated dosing machine was developed, incorporating:

- A 2- to 5-ton hopper with an anti-corrosive coating.
- A gravimetric dosing unit with 3 to 4 load cells and an expected accuracy of  $\pm 1.5\%$ .
- A pneumatic gate discharge system with a fine-control opening.
- A support structure with 3 meters of headroom and safe access points.
- A control panel featuring an Arduino Mega, a basic HMI, safety controls, and the option for digital logging or ticketing.
- A dust mitigation system using dust skirts and an extraction hood.
- Electrical and mechanical safety measures compliant with 220V/440V operation.

Based on the conceptual design, commercial components were selected and a scale prototype was built for initial testing.

A simulation and time estimation were then performed, comparing the manual method with the automated one. Based on the capabilities of commercial conveyors, it was estimated that a 1-ton load could be completed in 4 to 6 minutes, compared to 10 to 15 minutes for the manual system, representing a 25% to 60% time savings.

Finally, a preliminary economic evaluation was conducted, estimating a total system cost between \$300,000 and \$500,000 MXN. With approximate labor savings of \$100,000 MXN per season and increased machinery availability, a payback period of 2 to 4 years was projected for intensive-use operations. For small businesses, the payback period would be longer; therefore, shared-use models are suggested to improve profitability.

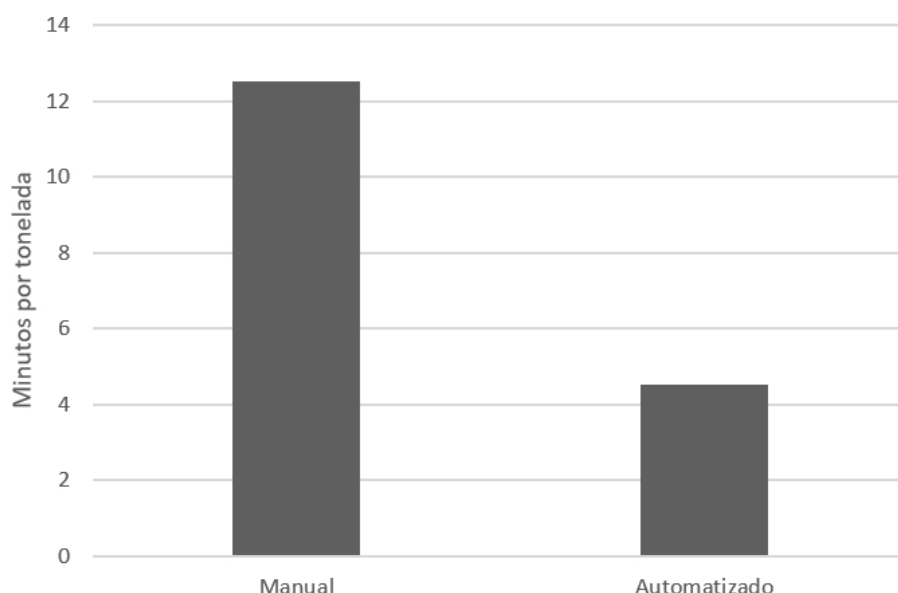
Overall, this methodology integrates qualitative research, engineering design, and economic analysis, laying the groundwork for the final proposal of the automated dosing machine prototype.

## Results and Discussion

Although this study focused on design and simulation, it is possible to anticipate the quantitative and qualitative effects of implementing the automated dosing system by comparing it with the traditional method. Thus, while the technical feasibility of the automated dosing system has been demonstrated at the conceptual level and through a functional prototype, its practical adoption may face various economic, operational, and human challenges that go beyond engineering considerations.

Reduction in loading times: the manual method requires between 10 and 15 minutes per ton with 2 to 3 operators, while the automated system could complete the task in 3 to 6 minutes, depending on the conveyor. This implies a **25% to 60%** savings, allowing for more fertilization trips per day and covering larger areas within the optimal application window.

Figure 1 shows the average times in minutes per ton of fertilizer unloading for each method, manual and automated. We observe that the automated method significantly reduces the average time, while manual unloading increases these times.

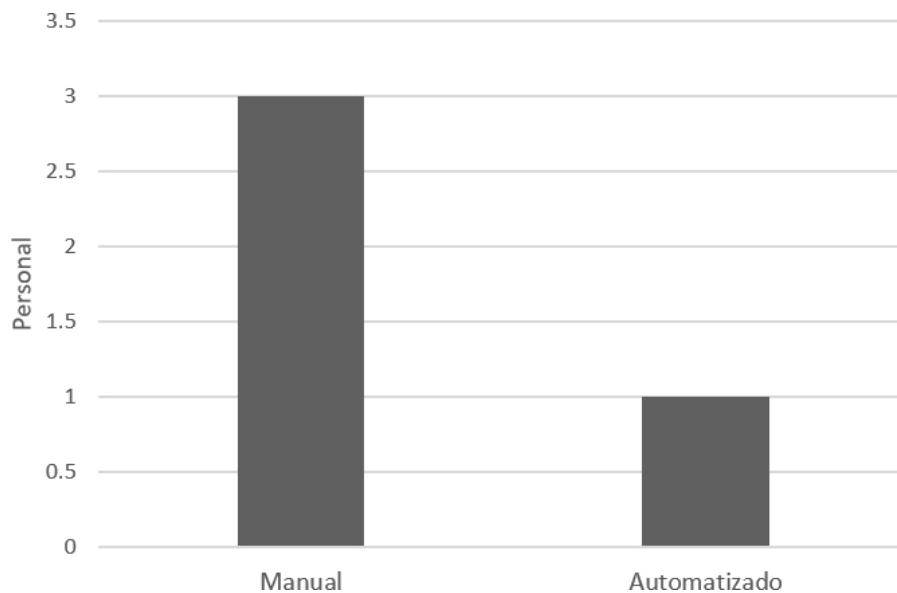


**Figure 1.** *Unloading time in minutes per ton: Manual vs. Automated.*

Automation is most cost-effective when there is a high daily throughput of loads, which is typical during planting and fertilization seasons. During periods of low demand, the equipment may be underutilized. As an alternative, we suggest a **shared-service** model among producers or the creation of mobile teams that serve multiple locations, thereby optimizing system utilization.

Automation reduces the workforce from 2 to 3 people to a **single operator**, with occasional assistance to refill the main hopper. This lowers labor costs and frees up staff for other critical tasks during peak seasons.

Figure 2 shows the number of personnel required for fertilizer unloading under each method, manual and automated. We found that the automated process can reduce labor requirements to just one person, whereas manual operation would require up to three personnel for proper execution.

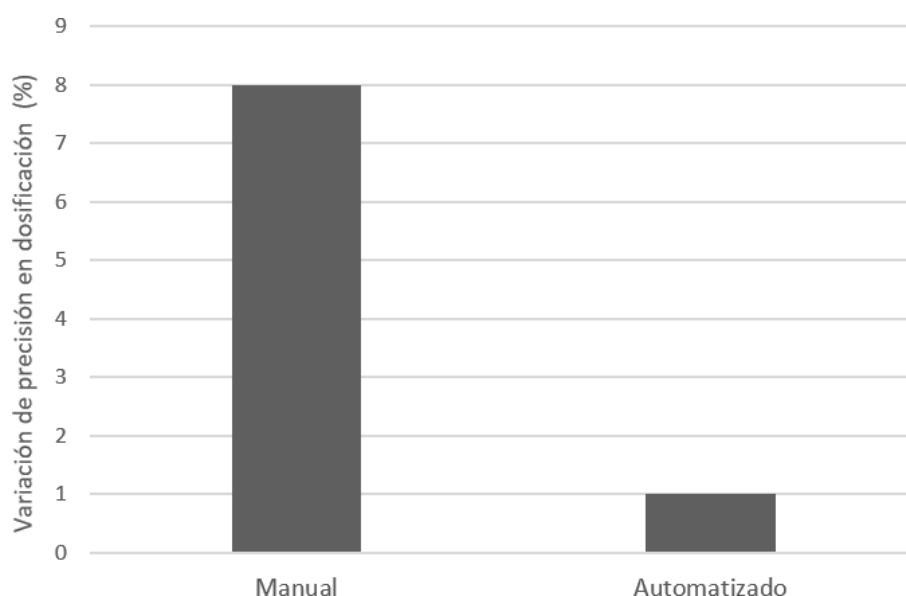


**Figure 2.** *Labor Requirements: Manual vs. Automated.*

Automation can create perceptions of job displacement, although the shortage of trained personnel during peak seasons suggests that the intention is to **reassign** staff to higher-value-added tasks, such as supervision, mix preparation, or maintenance. Early training and staff involvement in pilot phases promote acceptance, especially when improvements in safety and reduced physical exertion are evident. Dosing accuracy is also improved: while manual dosing has variations of  $\pm 5$  to 8%, the automated gravimetric system can achieve accuracies of  $\pm 1$  to 1.5%, consistent with precision agriculture standards. Greater accuracy yields direct benefits:

- Less fertilizer waste and reduced environmental risks.
- Greater uniformity in crop development.
- Better cost control of inputs by applying only the necessary amount.

Figure 3 shows the percentage variations in accuracy in the fertilizer discharge dosing process for each method—manual and automated. We can conclude that automation results in a variation in discharge accuracy of up to 1%, whereas performing this process manually can increase this variation to as much as 8% at the time of dosing.



**Figure 3.** *Variation in dosing accuracy: Manual vs. Automated.*

Flow behavior varies depending on the type of fertilizer, its particle size, and moisture content. Although the design incorporates vibration and geometry to ensure bulk or continuous flow, it will be necessary to adjust operating parameters and recalibrate the load cells when changing materials. It is recommended to test the system during the pilot phase with the main formulations used in the region to ensure stable operation.

By eliminating manual handling of bags, musculoskeletal risks, falls, and exposure to chemical dust are reduced. The operator works at a safe distance from the discharge point and under controlled conditions, complying with the guidelines of **NOM-006-STPS** on the handling of heavy materials. This contributes to a safer, healthier, and more professional operation.

Integration with mobile apps and the ability to connect the dispenser to cloud platforms open the door to future applications: synchronization with variable-rate fertilization systems, automation of input orders, or integration with agricultural logistics platforms. These advancements align with smart agriculture trends and could expand as technology adoption in the sector matures.

Similarly, we enhance traceability and inventory management, as each load is automatically recorded (date, weight, user, and customer/batch), which allows for:

- Tracking actual consumption and available stock.
- Generating receipts or invoices for internal or external customers.
- Analyzing usage patterns to optimize logistics and service scheduling.

Additionally, these records facilitate audits and reduce disputes over discrepancies in delivered quantities.

In addition to measurable benefits, automation enhances service professionalism through digital records, transparency in deliveries, and a reduction in disputes over quantities. It also strengthens workplace safety and regulatory compliance, contributing to a stronger corporate reputation. On the other hand, there are economic viability and productivity improvements; although the initial investment may be high for small businesses, the savings in time and labor, combined with increased operational capacity, allow for a projected return on investment of **2 to 4 years** in high-volume operations. In companies with many daily shipments, reducing each operation by 5 to 10 minutes can translate into additional hours of effective work per day. Added to this is the intangible value generated by greater accuracy, professionalization of service, and a reduction in complaints thanks to traceability.

The initial cost of automation can be high for small businesses accustomed to manual loading methods, which are perceived as low-cost. This resistance is reinforced by entrenched practices and an underestimation of the operational benefits. However, in larger-scale businesses or agricultural service centers, where high volumes are handled, the investment can pay for itself quickly and generate competitive advantages. Therefore, the initial rollout could focus on stakeholders with greater capacity for adoption or through demonstration pilot projects.

To date, no industrial-scale field tests have been conducted. The results are based on simulations and a small-scale prototype, so it will be necessary to validate performance under real-world conditions, particularly regarding extended work cycles, potential failures, voltage fluctuations, and long-term mechanical behavior. For industrial use, it will be necessary to properly size motors, implement certified scales for commercial transactions, and migrate from Arduino to an industrial PLC. However, the general architecture of the system remains valid and scalable.

## CONCLUSIONS

The development of the automated fertilizer dispenser prototype demonstrates the technical feasibility and potential operational impact of automation in the dispensing and loading of fertilizers in northern Sinaloa. The study's results lead to the following conclusions: Automation can reduce loading times by 25 to 40%, increasing machinery availability and accelerating fertilization tasks during critical periods, thereby improving the overall efficiency of the agricultural process. The proposed gravimetric system achieves a dosing accuracy with an error of approximately  $\pm 1\%$ , significantly better than manual methods. This promotes uniform nutrient distribution, minimizes waste, and reduces the environmental impact associated with over-application. By eliminating the manual handling of heavy loads, risks of injury, accidents, and exposure to chemical dust are reduced. This change improves working conditions and contributes to compliance with NOM-006-STPS regarding safe material handling. Digitizing load records allows for the documentation of the date, weight, and destination of each operation, enhancing transparency, internal control of inputs, and the foundation for smart agriculture systems. In medium or large companies, or under shared schemes, automation can pay for itself within an estimated 2 to 4 years, especially when high daily volumes of fertilizer are processed. The project tests the applicability of Industry 4.0 technologies in the local agricultural sector, integrating microcontrollers, sensors, and IoT. This opens opportunities for future improvements in mechanization, monitoring, and data-driven decision-making.

The main challenges to adoption are not technological, but rather economic, organizational, and human. The technology is viable and consistent with global trends in agricultural automation, but its successful implementation will depend on effective change management, training programs, and the implementation of pilot projects that tangibly demonstrate its benefits. Finally, the automated dispenser meets the objectives of increasing efficiency, accuracy, and safety in fertilizer loading, positioning itself as a solution aligned with precision agriculture and regional sustainability. Its successful implementation will depend on adaptation to each company's capabilities and proper change management, but it represents a promising alternative for strengthening agricultural competitiveness in northern Sinaloa.

Another relevant aspect emerging from the analysis is the technological scalability of the proposal. Although the prototype was designed using an Arduino microcontroller due to its flexibility and low cost, the proposed architecture allows for a progressive evolution toward more advanced industrial control platforms.

robust systems, such as certified PLCs and HMI systems. This feature represents a strategic advantage, as it enables agricultural businesses of all sizes to start with an affordable solution and then scale it up as their operational, security, and integration requirements with other production processes grow. Consequently, the proposal should not be viewed merely as an isolated prototype, but rather as the foundation of a scalable automation system adaptable to different levels of technological advancement.

In addition to the observed technical benefits, the implementation of an automated dosing system can generate a significant organizational impact within agricultural enterprises. The automation of the process not only transforms the loading operation but also fosters a work culture oriented toward standardization, control, and data-driven decision-making. This promotes the professionalization of staff, improves logistics planning, and reduces empirical practices that have historically limited operational efficiency. From this perspective, the proposed innovation contributes to the comprehensive modernization of agricultural management, strengthening regional competitiveness in a context where efficiency, traceability, and resource optimization are increasingly decisive factors.

Finally, the proposed system opens the door to broader smart agriculture frameworks, in which automated dosing is not an isolated process but rather part of a digital ecosystem for monitoring and managing inputs. Future integration with databases, complementary sensors, mobile platforms, and even communication protocols such as MQTT would provide real-time information to evaluate consumption, plan refills, generate operational histories, and improve the traceability of the fertilizers used. This technological evolution would not only strengthen operational control but would also have favorable implications in terms of sustainability by promoting a more rational use of inputs and reducing losses associated with dosing errors or inefficient manual handling.

## **FUTURE WORK**

An analysis of current practices in the loading of solid fertilizers in the northern region of Sinaloa highlights the need to move toward automated systems that improve efficiency, precision, and safety in agricultural operations. Based on the design of a microcontroller-based

and supervised via a mobile app, various lines of research and development are opened up that can strengthen technological innovation in the regional agricultural sector.

### 1. Technical Optimization of the Prototype

System scalability: Adapt the prototype for different load capacities and types of fertilizer.

Integration of advanced sensors: Incorporate machine vision technologies or moisture sensors to adjust the dosage based on input conditions.

Energy efficiency: Evaluate the use of renewable energy (solar panels) to ensure autonomy in rural areas.

### 2. Field Evaluation and Empirical Validation

Pilot tests at agricultural enterprises: Implement the prototype in real-world scenarios to measure loading times, accuracy, and reduction of occupational hazards.

Comparison with traditional practices: Document improvements in productivity and ergonomics compared to manual bag handling.

Cost-benefit analysis: Determine the economic viability of widespread adoption of the system.

### 3. Expansion into Digital Ecosystems

Remote monitoring platforms: Develop mobile applications with traceability features and automatic reporting.

Integration with agricultural management systems: Connect the dispenser to crop planning and inventory control software.

Use of IoT and Big Data: Generate databases on fertilizer consumption for predictive analysis and resource optimization.

### 4. Social and Organizational Impact

Training for agricultural staff: Design training programs on the use of automated technologies.

Reduction of occupational risks: Evaluate improvements in occupational safety and health resulting from reduced physical exertion and exposure to dust.

Cultural shift in technology adoption: Promote acceptance of automation through awareness campaigns and practical demonstrations.

## 5. Regional and National Scope

Replication in other crops and regions: Extend the model to different agricultural contexts within and outside of Sinaloa.

Collaboration with academic institutions and research centers: Strengthen innovation through joint projects.

Supportive public policies: Promote financing programs and subsidies for the adoption of automation technologies in the Mexican agricultural sector.

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