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Environmental Assessment in Pear Cactus Cultivation Using IoT + Edge AI

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Abstract. A prototype based on Internet of Things (IoT) technology is presented, featuring an embedded fuzzy system that enables real-time evaluation of the condition of a nopal crop. The study analyzes the required environmental and soil conditions for optimal growth. Although the work focuses on assessing these conditions, it also considers the plant's overall health status. The presented experiments demonstrate the feasibility of evaluating nopal crops. The proposed module can be installed on a mobile robot, allowing for plant-by-plant inspection.

Keywords: IoT, edge AI, fuzzy systems, digital agriculture.

1 Introduction

1.1 Cactus Pear Uses

Cactus pear (nopal) is a versatile plant with various applications in different fields. Below are some of its most common uses [7]:

- **Culinary Uses**: Nopal pads (cladodes) and prickly pear fruits are widely consumed. They can be eaten fresh, cooked, or juiced and are commonly used in salads, stews, jams, and beverages due to their nutritional benefits.
- **Medicinal Uses**: Nopal has several potential health benefits, including:
  - Lowering blood sugar levels.
  - Reducing cholesterol.
  - Aiding digestion.
  - Possessing anti-inflammatory properties.
- **Cosmetic Uses**: Extracts from nopal are incorporated into skincare products for their hydrating, anti-aging, and soothing effects on irritated skin.
- **Animal Feed**: Nopal pads serve as a nutritious fodder option for livestock, particularly in arid regions where other feed sources are scarce.

- **Industrial Uses**: The mucilage from nopal has various industrial applications, including:
  - Water purification.
  - Bioplastics production.
  - Use as a natural thickener.
- **Environmental Uses**: Nopal plays a role in soil conservation, combating desertification, and carbon sequestration due to its resilience in harsh climatic conditions.

1.2 Factors which Affect the Crop Quality of Cactus Pear

Several factors influence the crop quality of cactus pear (Opuntia spp.), commonly known as nopal. Environmental conditions such as temperature, rainfall, and soil type play a crucial role, as nopal thrives in arid and semi-arid regions with well-drained, sandy-loam soils. Water availability is particularly important since drought stress can reduce pad and fruit quality, while excessive moisture may lead to fungal diseases. Proper nutrient management, especially adequate levels of nitrogen, phosphorus, and potassium, enhances growth and fruit development. Additionally, pests and diseases, including cochineal insects and fungal infections like Phyllosticta and Colletotrichum, can significantly impact yield and quality. Cultivation practices such as pruning, spacing, and harvesting techniques also contribute to the final product's texture, size, and nutritional value. Lastly, genetic factors and the choice of cultivar determine resistance to stress conditions and overall market appeal.

1.3 Uses of IoT for Digital Agriculture

The Internet of Things (IoT) is revolutionizing digital agriculture by enabling real-time monitoring, automation, and data-driven decision-making. IoT-powered smart sensors track soil moisture, temperature, and nutrient levels, allowing farmers to optimize irrigation and fertilization, reducing waste and improving crop yields. Automated irrigation systems adjust water distribution based on weather and soil conditions, conserving water while ensuring optimal plant growth. In livestock management, IoT wearables monitor animal health, movement, and feeding patterns, enhancing productivity and disease prevention. Drones and smart machinery automate planting, spraying, and harvesting, increasing efficiency and reducing labor costs. Additionally, IoT-enabled supply chain tracking ensures transparency in food production, while AI-powered predictive analytics help farmers make better decisions based on climate and market trends. By integrating IoT, agriculture becomes more sustainable, efficient, and profitable, addressing global food security challenges while minimizing environmental impact [8, 10, 11, 6, 5].

1.4 Motivations

Crop quality evaluation is a critical aspect of modern agriculture, ensuring that produce meets industry standards and consumer expectations. This process involves assessing various factors such as plant health, growth rate, nutrient levels, and resistance to pests or diseases. Advanced technologies, including remote sensing, IoT-based monitoring, and machine learning algorithms, enhance precision in evaluating crop conditions in real time. Traditional methods, such as visual inspection and laboratory testing, are also used to analyze soil composition, moisture content, and overall plant vitality. By implementing efficient crop quality evaluation techniques, farmers can optimize yield, reduce losses, and maintain sustainable agricultural practices.

2 Hierarchical Fuzzy System for Crop Quality Evaluation

Fuzzy systems can be effectively used to analyze crops, particularly cactus pear. Since much of the knowledge related to crop evaluation is linguistic, fuzzy rules provide an ideal way to represent this information. These rules incorporate data from various sensors, including temperature, humidity, and soil characteristics, to assess and qualify the environmental conditions of the crop. This approach enables a more precise and adaptable evaluation, improving decision-making in agricultural management $[4, 3, 9, 1, 2]$.

A Hierarchical Fuzzy System (HFS) for crop quality evaluation can be mathematically defined as a multi-level fuzzy inference system, where the output of one fuzzy system serves as an input for another. This hierarchical structure reduces complexity and improves interpretability by separating the evaluation process into smaller, manageable sub-systems cite.

2.1 Mathematical Definition

Input Variables Let $X = \{x_1, x_2, \ldots, x_n\}$ be the set of input variables representing crop attributes. Each input x_i is fuzzified using membership functions $\mu_{A_i}(x_i)$, where A_i is a fuzzy set.

Fuzzy Rules At each level l, the fuzzy rules are defined as:

$$R_k^{(l)} : \text{IF } x_1 \text{ is } A_{k1}^{(l)} \text{ AND } x_2 \text{ is } A_{k2}^{(l)} \text{ AND } \ldots \text{ AND } x_n \text{ is } A_{kn}^{(l)} \text{ THEN } y_k^{(l)} \text{ is } B_k^{(l)}, \quad (1)$$

where:

- $R_k^{(l)}$ is the k-th rule at level l,
- $A_{ki}^{(l)}$ are fuzzy sets for input x_i at level l,
- $y_k^{(l)}$ is the output of the k-th rule at level l,
- $B_k^{(l)}$ is the fuzzy set for the output at level l.

Hierarchical Structure The output of level l becomes the input for level $l+1$. The final output Y is obtained at the last level L:

$$Y = f^{(L)}(f^{(L-1)}(\ldots f^{(1)}(X))),$$

where $f^{(l)}$ is the fuzzy inference function at level l.

Defuzzification The final output Y is defuzzified using the centroid method:

$$Y_{\text{final}} = \frac{\int y \cdot \mu_Y(y)\, dy}{\int \mu_Y(y)\, dy},$$

where $\mu_Y(y)$ is the membership function of the final output.

2.2 Hierarchical Architecture

A hierarchical fuzzy system that evaluates the conditions of a nopal crop, an embedded fuzzy system is implemented within an Internet of Things (IoT) module. The architecture is shown in Figure 1. Five signals are considered to evaluate the quality of the environment (soil and atmosphere) in which the nopal crop is grown. The rules are designed taking these aspects into account, as the plant is more resistant to droughts and high temperatures, as mentioned above. To avoid the combinatorial explosion of rules, which would require including $5 \times 5 \times 5 \times 5 \times 5 = 3125$ rules, the fuzzy system with five inputs is transformed into two fuzzy systems: one with two inputs to determine the soil quality of the crop, and another with three inputs to evaluate the environment where the crop is located. The total number of rules is drastically reduced to $5{\times}5{\times}5{+}5{\times}5 = 150$ rules in total. A hierarchical fuzzy system is shown in Figure 5.

This architecture simplifies rule generation and significantly reduces the number of rules required. For instance, a rule to determine soil quality considers moisture and pH levels. In nopal (cactus pear) crops, an intermediate pH combined with low to medium moisture is ideal for enhancing soil quality. Similarly, a high or very high-quality crop environment is generally preferred for optimal growth. However, nopal crops can demonstrate resilience even in environments with medium or low quality.

3 Experimentation and Results

3.1 First Simulation: 24-Hour Evaluation

The first simulation involves a 24-hour evaluation, considering the average weather conditions in the metropolitan area of Nuevo León. The evaluation takes into account the type of soil present, which is exposed to various environmental conditions such as rain and wind, affecting its moisture and pH composition, although the latter changes only slightly.

3.2 Nopal's Resilience and Evaluation Results

The nopal is a highly drought-resistant plant, capable of withstanding extreme conditions. It is expected that under very low light conditions, the cultivation conditions are very poor; the evaluation system reflects this. Under better lighting conditions, these conditions improve significantly. However, even then, it barely surpasses a rating of 7 out of 10. Figure 3 shows the performance of the system evaluation.

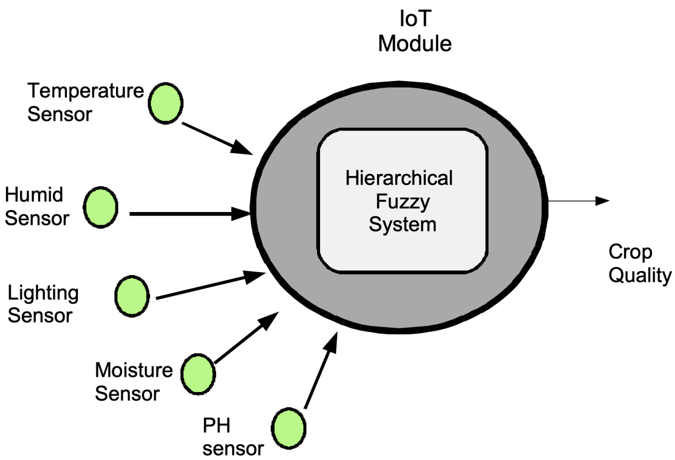

Fig. 1. IoT Module for evaluation of environment and soils of crops.

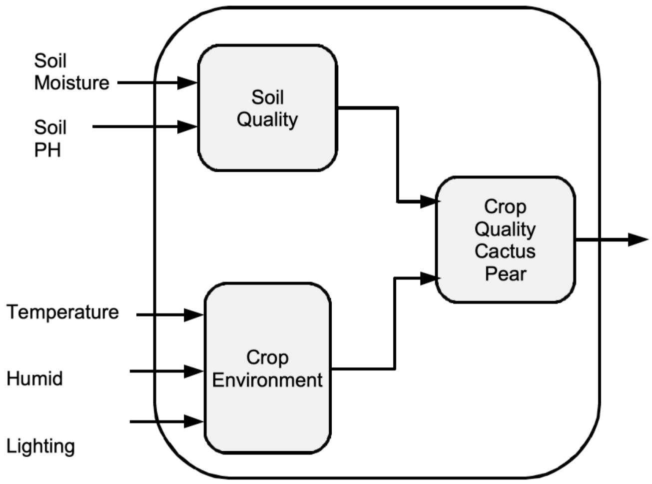

Fig. 2. Evaluation system based on a hierarchical fuzzy system.

3.3 Optimization Using the Evonorm Algorithm

Using an optimization algorithm based on the Evonorm algorithm [12], the ideal conditions to achieve a rating of 87 are as follows:

- Temperature: 21.79
- Humidity: 44
- Light intensity: 40233

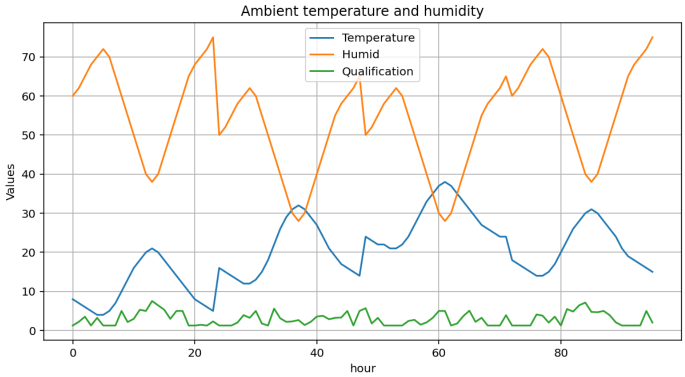

Fig. 3. Evaluation system based on a hierarchical fuzzy system.

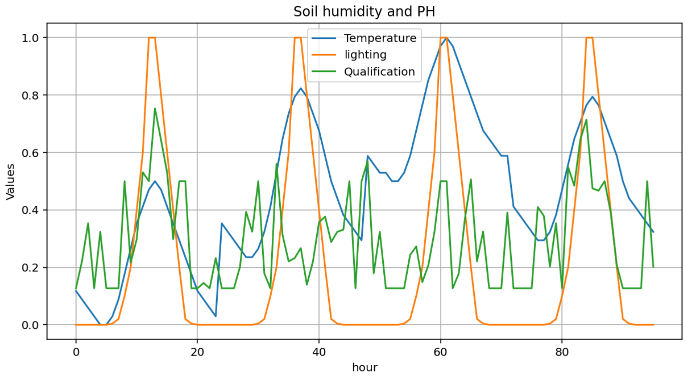

Fig. 4. Evaluation system based on a hierarchical fuzzy system.

- Soil moisture: 39.45
- Soil pH: 7.52

3.4 Considerations for Ideal Conditions

It is important to note that achieving these ideal conditions is very difficult unless additional measures are applied, such as fertilizers, irrigation systems, or greenhouse cultivation.

4 Conclusion

The nopal is a resilient plant that can adapt to less-than-ideal growing conditions. However, to maximize its growth and production, it is important to ensure that the conditions mentioned above are optimal. Monitoring and

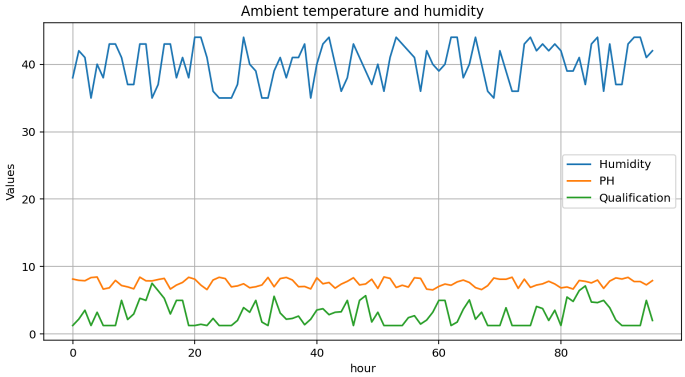

Fig. 5. Evaluation system based on a hierarchical fuzzy system.

adjusting these factors will significantly contribute to the success of nopal cultivation.

Exposure to air pollutants such as alcohols, methane, and hydrocarbons can be harmful to nopal crops, affecting their health, growth, and productivity. Implementing appropriate management strategies and continuous monitoring can help mitigate these effects and promote healthier, more productive cultivation.

Airborne particulate matter poses a significant risk to the health and productivity of nopal crops. Understanding and mitigating the impacts of this type of pollution is crucial to maintaining plantation health and the quality of derived products.

The presented module demonstrates the feasibility of implementing a crop evaluation system focused on nopal cultivation. The results obtained allow for application to extensive crops, as the system can be mounted on a robot and perform plant-by-plant inspections. The issue of environmental contamination remains a challenge, particularly regarding the use of more sophisticated sensors or for crops that require greater care. Finally, this system can be extended to other crops, considering modifications in the rules, as each type of plant has specific care requirements.

A hierarchical fuzzy system provides a robust framework for evaluating crop quality by systematically processing multiple attributes at different levels. This approach handles uncertainty and complexity effectively, making it suitable for use in portable devices, inclusive of drones or autonomous vehicles.

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