Edge AI-Driven Targeted Fertilizer Dispensing System for Mid-Sized Oil Palm Plantations Using Sensor Fusion

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Abstract

Nutrient management in commercial oil palm plantations presents a significant logistical challenge. Manual fertilizer application is labor-intensive and inefficient, while conventional tractor-mounted broadcast spreaders lead to substantial material wastage. These standard machines dispense fertilizer in a 360-degree pattern, causing much of the nutrient load to fall in inter-row spaces where it encourages weed growth rather than crop development. To address these inefficiencies for mid-sized operations, this paper proposes a low-cost, automated fertilizer dispensing system utilizing Edge AI and sensor fusion [4]. The architecture incorporates a Raspberry Pi 4B integrated with an HC-SR04 ultrasonic sensor for proximity measurement and a Pi Camera executing a lightweight YOLOv8 object detection model for real-time oil palm trunk identification [1]. Upon detection of a tree within a 2.5-meter threshold, the system activates a 12V linear actuator to open a targeted chute, delivering a precise dose of granular fertilizer directly to the weeded root basin. The design further includes a mechanical agitator within the hopper to prevent clumping of hygroscopic fertilizers. Initial benchtop evaluations indicate that affordable edge computing devices can achieve the requisite low-latency performance for precision agricultural applications. This system offers a scalable bridge between manual labor and high-cost commercial spreaders, significantly reducing fertilizer waste and operational overhead.

1. Introduction

Getting fertilizer placement right is one of the most important factors for maximizing fresh fruit bunch (FFB) yields in oil palm farming [5]. However, the standard layout of an oil palm plantation makes mechanization difficult. Trees are typically planted on a 9-meter grid, but the active feeding roots of juvenile and early-yielding palms stay tightly clustered in a 1.5 to 2-meter radius around the trunk.

Right now, farmers mostly rely on manual labor to walk the fields and drop fertilizer near the base of each tree. As labor becomes harder to find, many look to tractor-mounted centrifugal spreaders to speed things up. The problem is that these spreaders just throw fertilizer everywhere. Applying a fixed rate across the entire field means you are over-applying in the empty grass rows and under-applying where the roots actually live.

Edge computing and local AI offer a highly practical way out of this trap. This project details the design of a smart, tractor-mounted dispensing chute that knows exactly when to drop fertilizer. By pairing simple distance sensors with a YOLOv8 vision model running locally on a Raspberry Pi, the machine can autonomously detect the tree trunks as it drives past and release the fertilizer only into the active root zone.

2. Related Work

Machine learning in agriculture is moving quickly from cloud-based analysis down to hardware running on the edge. The "You Only Look Once" (YOLO) architecture, in particular, has become the go-to standard for identifying objects in messy, outdoor farm environments [1].

Recent field studies show that the YOLOv8-nano model is exceptionally good at finding oil palm trees, even when deployed on small hardware [2], [3]. For instance, tests running YOLOv8n on a Raspberry Pi 4B hit over 95% precision with inference speeds fast enough to keep up with a moving vehicle. On the mechanical side, agricultural trials have repeatedly shown that switching to mechanized row-banding can boost a farm worker's coverage from about 2 hectares a day to over 25 hectares, while cutting overall fertilizer waste by up to 20% [5].

3. System Architecture

This system ditches the traditional spinning broadcast disc in favor of a gravity-fed chute, controlled by split-second electronic timing.

3.1 Edge AI Control Unit

The brain of the operation is a standard Raspberry Pi 4B (4GB RAM). It packs enough processing power to run the neural network locally, meaning the tractor does not need a cellular internet connection out in the field.

3.2 Sensor Fusion Hardware

Relying on just one sensor out in a farm field usually leads to false triggers—like dispensing fertilizer because a worker walked past the tractor. To fix this, we use a two-step verification process [4]:

- **Proximity Check:** An HC-SR04 ultrasonic sensor is mounted on the side of the tractor, constantly measuring the distance to the tree row.
- **Visual Check:** A Pi Camera sits next to the ultrasonic sensor. It stays dormant to save processing power until the proximity sensor tells it to wake up and look.

3.3 Dispensing and Anti-Jamming Mechanics

Standard gravity hoppers jam easily because fertilizers like Urea and DAP absorb humidity from the air and turn into solid clumps. To handle real-world conditions, the hardware includes two main modifications:

- **Actuated Chute:** The drop pipe is fitted with an electronic butterfly valve controlled by a 12V linear actuator for fast, precise opening and closing.
- **Agitator:** A high-torque, 12V DC motor runs a steel star-wheel inside the hopper at roughly 60 rpm. This slowly stirs the fertilizer at the bottom, breaking up any clumps before they can reach and block the chute.

4. Methodology and Logic Flow

The software is a lightweight Python loop designed to run with very low latency while the tractor is in motion.

1. **Standby:** The ultrasonic sensor pings the area to the side of the tractor. If it reads a distance greater than 3 meters, the system loops and does nothing.
2. **Detection:** As the tractor pulls up next to a tree, the distance reading drops below 2.5 meters.
3. **Verification:** This distance drop triggers the Pi Camera to take a frame and push it through the YOLOv8 model.
4. **Action:** If the AI is at least 85% confident that it is looking at an "Oil Palm Trunk," the Raspberry Pi triggers a 5V relay.
5. **Dispensing:** The relay sends power to the linear actuator, pulling the chute open for exactly enough time (e.g., 1.5 seconds) to drop a 1-kilogram dose into the weeded basin, before snapping back shut.

5. Expected Impact and Discussion

Building this kind of targeted dispensing system directly solves the biggest headaches for mid-sized plantation management. By dropping the fertilizer only in the 2-meter root basin, farmers stop paying to fertilize their weeds.

Targeted application practices like this have historically reduced total nitrogen use by 15% to 35% compared to broadcast spreading [5]. It also removes the physical bottleneck of manual labor. A single tractor driver can cover the acreage of a whole team of workers, but maintain the exact same per-tree precision that you would get from doing it by hand.

6. Conclusion

The "Targeted Fertilizer Dispenser (TFD)" prototype proves that precision agriculture does not have to cost thousands of dollars or be limited to massive corporate farms. By combining cheap, off-the-shelf edge computing like the Raspberry Pi with efficient vision models like YOLOv8, local farmers can build highly accurate tools. This sensor-fusion approach stops fertilizer waste, solves labor shortages, and guarantees that expensive nutrients end up exactly where the trees can actually use them. Future steps for this project will involve field-testing the hopper mechanics on a tractor and logging the dispensing data to a cloud dashboard for inventory tracking.

References

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