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# REDUCING GROUND LOSSES USING A LEAF SEGMENTATION-BASED AUTONOMOUS SPRAYER FOR PAPAYA GREENHOUSES

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## ABSTRACT

Papaya plants have irregular canopy structures, making traditional spraying methods highly labour-intensive and prone to chemical waste due to non-selective application. In precision agriculture, delivering pesticides accurately to target areas is crucial for reducing labour requirements, costs, and environmental impact. Therefore, the integration of smart agricultural machinery and machine vision is necessary to optimise pesticide application. In this study, a low-cost autonomous spraying system that integrates deep learning-based papaya leaf segmentation with a lightweight, two-degree-of-freedom (DOF) robotic arm mounted on a mobile platform was developed and evaluated in the papaya greenhouse. Inspired by wrist-like human spraying motion, the 2-DOF robotic arm dynamically adjusts to leaf positions identified by a machine vision system. Unlike conventional static systems, the proposed solution dynamically adapts to complex plant morphologies to perform selective, leaf-level spraying. The results of the segmentation model achieved over 70% accuracy under real-world conditions. In comparison with manual spraying, the autonomous spraying system achieved similar performance in terms of droplet diameter, coverage, and spray deposition. Moreover, it reduced ground-level loss by 39%. An affordable autonomous spraying robot demonstrates strong potential to replace conventional spraying methods, particularly in medium- and small-scale farming.

**Keywords:** autonomous spraying, machine vision, papaya greenhouse, robotic arm

## INTRODUCTION

Irregular structure and dense canopy of papaya plants hinder the effective use of mechanised spraying systems. Consequently, traditional methods such as knapsack sprayers are commonly employed. These conventional approaches are typically continuous and non-selective, resulting in excessive chemical residues in both the crops and the soil (Jat et al., 2023). Automation and precision agriculture offer a promising solution by reducing labour demands and minimising environmental impact. Recent efforts have focused on developing selective spraying systems that adapt to plant morphology using sensors or cameras to detect features such as plant height, canopy width, and area (Abbas et al., 2020; Nguyen et al., 2023). However, most of these systems are designed for crops with relatively flat and uniform canopies, where detection is straightforward. In contrast, papaya leaves vary greatly in shape,

size, and 3D distribution, posing challenges for accurate leaf-level targeting.
To address this challenge, the present study employs real-time instance segmentation to identify individual leaves at the pixel level. When combined with depth data from an RGB-D camera, this approach enables accurate detection of the spatial morphology and orientation of papaya leaves. A robotic arm is then integrated to adjust spray positions based on the segmentation results dynamically. Designed with two degrees of freedom that replicate human wrist movements, including flexion and extension (FE) and radial and ulnar deviation (RUD), the arm can adapt to the complex canopy structure. Additionally, a motion learning algorithm is implemented to replicate expert spraying behaviours, allowing the robot to adjust its trajectory in response to leaf position and improve spraying precision in complex agricultural environments.

## MATERIALS AND METHODS

The autonomous spraying robot consists of a vision computing unit, spraying mechanism, robotic arm control, wrist sensing unit, and mobile platform. An RGB-D RealSense D455 camera paired with an NVIDIA Jetson Xavier is used to detect and segment papaya leaves in real-time. The robotic arm, driven by two stepper motors and 1:20 gearboxes, replicates human wrist movements through two DOF: FE and RUD. Joint limits, defined based on biomechanical studies, constrain the motion of the robot arm within a human-like range and are used to construct the manipulator's transformation matrix for accurate and adaptive control. Human spraying demonstrations were recorded at 40 Hz using a wrist unit, and Dynamic Time Warping (DTW) was applied to align the variable-length time series. Generalised trajectories generated via Gaussian Mixture Model and Regression (GMM/GMR) were used to train the robot, enabling it to reproduce expert spraying motions in response to leaf positions. A field experiment was conducted to evaluate the system's practical performance compared to manual spraying methods.

## RESULTS & DISCUSSION

The automated spraying robot was tested in a papaya greenhouse to evaluate the spraying application. The end effector of the robot arm showed a repeatability error ranging from 0.1 cm to 7.5 cm. A YOLOv8s-Seg model was employed for papaya leaf segmentation and integration into the spraying system. Despite challenges from lighting and background complexity, the model achieved over 70% segmentation accuracy, confirming its effectiveness for real-time leaf detection in greenhouse conditions, shown in Fig. 1.

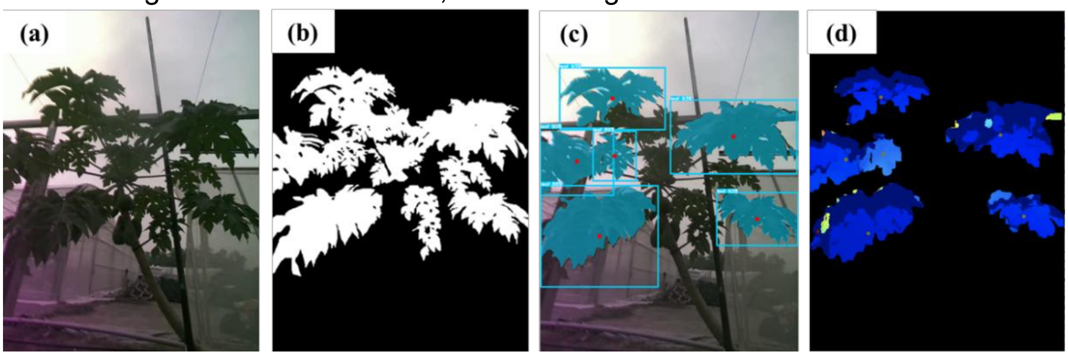


Fig. 1. Detection and segmentation results with the proposed method in the papaya greenhouse, (a) presents the RGB images captured, (b) ground truth binary masks annotated manually, (c) demonstrates the detection and segmentation results using our developed approach, (d) shows the fusion of segmentation and RGB-D data.

Greenhouse experiments presented challenges, including environmental complexity and limited data repeatability. To evaluate the real-world performance of the autonomous spraying system under these conditions, we focused on assessing spray effectiveness in terms of droplet size, density, and spatial distribution. Compared to manual spraying, the autonomous system produced finer droplets, resulting in improved surface coverage and higher uniformity, as shown in Table 1. Moreover, it demonstrated superior deposition efficiency, with ground deposition reduced by 39% relative to the knapsack sprayer. This reduction suggests more accurate canopy targeting and less chemical waste. The improved efficiency is largely attributed to the smaller droplet size, which enhanced canopy penetration while minimising ground loss.

Table 1 Comparison between knapsack sprayer method and autonomous spraying method

| Variables | Droplet coverage (%) | Droplet density (Number/$cm^2$) | Droplet diameter (μm) | Losses ground (μL/$cm^2$) |
|---|---|---|---|---|
| Knapsack sprayer | 23.1 ± 2.0 | 49.4 ± 9.6 | 360.1 ± 25.6 | 5.4 ± 0.4 |
| Autonomous spraying | 16.9 ± 0.6 | 54.6 ± 2.4 | 268.3 ± 9.7 | 3.3 ± 0.2 |

## CONCLUSIONS

This study presents a practical approach to an autonomous sprayer by combining machine vision and human-inspired robotic motion. The proposed system offers a scalable and low-cost solution for precision agriculture in complex greenhouse environments. Its successful implementation demonstrates the feasibility of replacing manual spraying with intelligent automation. Future research will focus on improving system adaptability and extending its application to other crop types.

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## REFERENCES

Anderson, G. T., C. V. Renard, L. M. Strein, and E. C. Cayo. 1998. A new technique for rapid deployment of rollover protective structures. Applied Eng. in Agric. 23(2): 34-42.

Abbas, I., Liu, J., Faheem, M., Noor, R. S., Shaikh, S. A., Solangi, K. A., & Raza, S. M. (2020). Different sensor based intelligent spraying systems in Agriculture. Sensors and Actuators A: Physical, 316, 112265. doi:https://doi.org/10.1016/j.sna.2020.112265

Jat, D., Dubey, K., Potdar, R. R., Chakraborty, S. K., Kumar, S. P., Chandel, N. S., . . . A, S. (2023). Development of an automated mobile robotic sprayer to prevent workers' exposure of agro-chemicals inside polyhouse. Journal of Field Robotics, 40(6), 1388-1407. doi:https://doi.org/10.1002/rob.22181

Nguyen, N. T. A., Pham, C. C., & Lin, W.-C. (2023). Development of a line following autonomous spraying vehicle with Machine vision-based leaf density estimation for cherry tomato greenhouses. Computers and Electronics in Agriculture, 215, 108429. doi:https://doi.org/10.1016/j.compag.2023.108429