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AUTONOMOUS AGRICULTURAL SPRAYING UAV: DESIGN, IMPLEMENTATION AND PERFORMANCE ANALYSIS

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Abstract: This article discusses the importance of spraying in precision agriculture to optimize land use, particularly in response to increasing population and declining agricultural land. A six-rotor unmanned aerial vehicle (UAV) was designed to maximize spraying efficiency and minimize waste. The required pesticide amount was determined based on the number of trees in the field, and UAV components capable of autonomous spraying were selected accordingly. Autonomous flight tests were conducted using a color-based object detection algorithm for tree identification. Success rates are calculated by the ratio of color-changing areas in images captured by the thermal camera to the total area. The results indicate that in low-wind conditions, the spraying success rate can reach 92%, whereas in high-wind conditions, it drops to 20%. Comparisons with traditional spraying methods reveal that tractor-based spraying achieves the same efficiency (92%) but requires 1.5 times longer spraying time and twice the pesticide amount. In contrast, hand-pump spraying reaches 97% efficiency but requires 7.5 times longer and consumes 3.5 times more pesticide. In addition, when comparing spraying to be done on large agricultural lands such as 10 acres, in addition to the amount of spraying and water, diesel fuel is added for spraying with a tractor, personnel costs are added for spraying by hand, while only the electricity cost to charge the battery is added for spraying with a UAV. The effect of wind speed on the success rate can be ensured by revising the UAV position after the calculations are made after the wind direction and speed are determined, and stability can be ensured in future studies.

Keywords: UAV, Precision agriculture, Spraying, Productivity, Autonomous

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1. Introduction

According to research by the world census companies (Attenborough D. 2024), the global population is expected to exceed 8 billion by 2024, and the effects of climate change are becoming increasingly evident (Iglesias et al., 1999). The increasing demand for food, combined with the limited availability of arable land, poses significant challenges to agricultural production. Agriculture, a practice that has been around for over 10,000 years (Hole, 1984), has seen continuous advances, including the development of irrigation systems, the initiation of the Green Revolution (Pimental, 1996), and the mechanization of farming techniques. In the contemporary era, increasing agricultural productivity and promoting sustainable farming practices have become essential to achieving global food security.

One of the most critical aspects of farming is pest control (Anonymous. 2024). Pesticides play a vital role in maximizing crop yield (Tudi et al., 2021); however, traditional spraying methods, such as manually operated sprayers and tractor-mounted sprayers, often lead to waste and environmental damage due to overuse or inefficiency (Jacquet et al., 2022). In response, modern farmers are increasingly adopting advanced technologies to enhance productivity and efficiency while minimizing waste (Arbat et al., 2024). Among these innovations, unmanned aerial vehicles (UAVs) have emerged as a key tool in precision agriculture (Velusamy et al., 2022).

This study focuses on the design and implementation of the Autonomous Intelligent Controlled Agricultural Spraying Unmanned Aerial Vehicle (UAV), known as SRUAV (a six-rotor Unmanned Aerial Vehicle), for precision pesticide application in agricultural environments, offering improved efficiency, accuracy, and sustainability compared to conventional methods. Given the challenges associated with fixed-wing UAVs such as the need for extensive piloting skills and long, smooth runways for takeoff and landing rotary-wing UAVs have been considered more suitable for this application.

Autonomous UAVs offer a transformative solution by enabling precision spraying (Alsalam et al., 2017). By accurately targeting specific areas or individual plants, UAVs can reduce pesticide usage, minimize environmental impact, and significantly decrease the time required for spraying.

This paper examines the technical design, mechanical and software aspects, and experimental results of the autonomous intelligent controlled agricultural spraying

UAV, SRUAV. To highlight its potential to revolutionize modern farming practices, tests were conducted under various weather conditions, and its performance was compared with traditional methods.

2. Materials and Methods

The six-rotor unmanned aerial vehicle, SRUAV, is designed to autonomously apply pesticides with the goal of maximizing efficiency and minimizing waste. The UAV is equipped with a range of advanced systems, including flight controllers, cameras, object detection algorithms, and pesticide spraying mechanisms (Figure 1). These components enable SRUAV to independently and accurately perform field spraying based on the number of trees and field dimensions. The overall structure of the drone consists of electronic equipment, a mechanical system, and a spraying system.

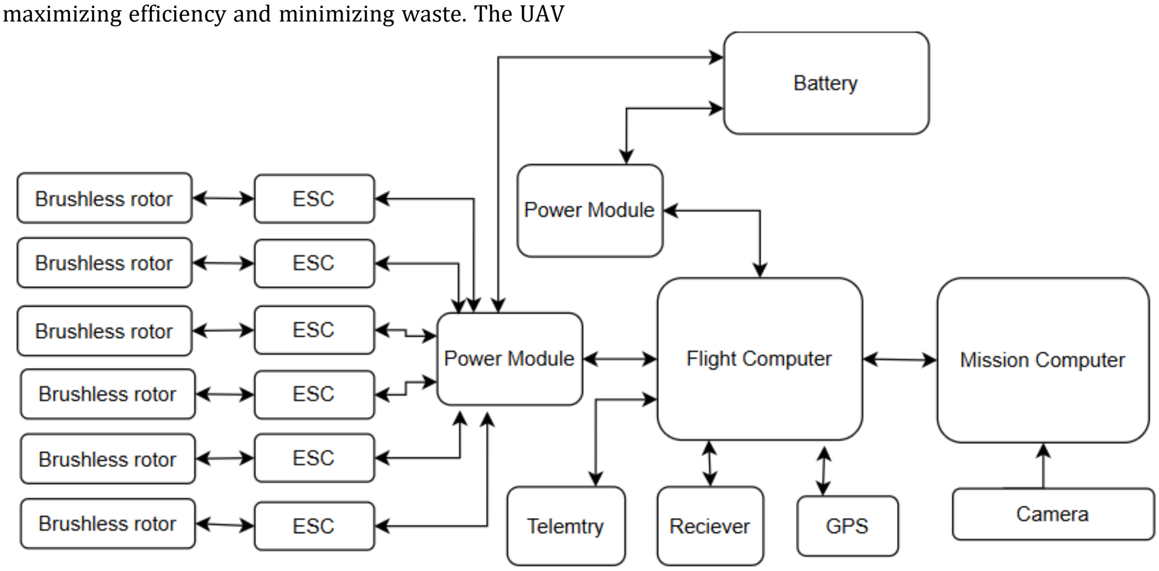


Figure 1. SRUAV avionics schematic.

2.1. Electronics Equipments

For optimal yield from trees, planting them at 5-meter intervals provides significant benefits (Arsov et al., 2019). The tests will be conducted on a designated one-acre plot containing 30 trees planted at 5-meter intervals. In spraying tests performed with independent spraying equipment from above, it was observed that when 150 ml of pesticide solution was applied to a single tree, the solution successfully penetrated the foliage, and the spraying process was completed within 5 seconds. For 30 trees, this amounts to 4.5 liters of pesticide solution, and the pesticide tank has been selected accordingly.

The total weight of the UAV, including the pesticide payload, electronic equipment, and chassis, is estimated to be approximately 12 kg. In the planned UAV design, after considering the weight-to-thrust parameters, the expected lift force is anticipated to be more than 4/3 of the total weight (Stamate et al., 2017). This corresponds to a total lift force of 16 kg, meaning that each motor must generate more than 2.67 kg of thrust.

After conducting market research, it was determined that the SunnySky X4112S 450KV motor meets the required thrust with 2.76 kg of output. The rotor weighs 188 g and operates with a 14-inch propeller. At maximum thrust, the rotor draws 23.2 A of current. Given these parameters, a 30A ESC is sufficient, making the 25 g Readytosky 30A ESC a suitable choice for this study.

In the flight scenario, the UAV requires 5 seconds to take off and reach the starting point of the field. For each designated waypoint, it takes 5 seconds to spray the identified trees, 8 seconds to move to the next tree, 10 seconds to return to the landing point after completing the spraying process, and 5 seconds for landing. The total current consumption of the UAV should be calculated using the following (equation 1):

$$I_{total} = I_{avionics} + I_{motor} \quad (1)$$

For the motor current calculation, the equation is given as (equation 2):

$$I_{motor} = \frac{t * 1000 * n * I}{k} \quad (2)$$

(Avşar et al., 2021) where:

- I_{motor} is the total current required by the motors,
- t is the total flight time in seconds,
- n is the number of motors,
- I is the current drawn by each motor at maximum thrust,
- k is the efficiency coefficient of the power system.

This equation ensures an accurate estimation of the required battery capacity to sustain the UAV's operation throughout the spraying mission.

To accurately determine the total motor current consumption, equation (2) must be applied separately for each UAV movement phase, considering the average current drawn for each action. The calculated current consumption for each phase of the UAV's operation is as follows:

- Takeoff: 187 mAh
- Tree-to-tree transition: 9040 mAh
- Tree spraying: 5200 mAh
- Returning to the starting position: 320 mAh
- Landing: 100 mAh

In total, throughout the flight duration, the rotors consume: $I_{motor} = 14\ 847\ mAh$.
The total equipment current consumption is calculated using the following equation (equation 3):

$$I_{equipment} = I_{orin} + I_{pixhawk} + I_{telemtry} + 2 * I_{led} + I_{spraying\ motor} \quad (3)$$

$$I_{equipment} = 6\text{A} + 2{,}5\text{A} + 1\text{A} + 2 * 0{,}5 + 6\text{A} = 16{,}5\text{A} \quad (4)$$

The battery current consumption is determined using the following (equation 5):

$$V_{battery} * I_{battery} = V_{equipment} * I_{equipment} \quad (5)$$

Since the selected battery is a 6S Li-Po, the battery voltage is 22.2V. The electronic equipment operates at 5V. Also equipment current is 16.5 A. Substituting these values into equation (5), the battery is expected to supply 3.72A to meet the power requirements of the electronic equipment. The current drawn by the avionics equipment from the battery is calculated using the following (equation 6):

$$I_{avionics} = \frac{I_{battery} * t * 1000}{c} \quad (6)$$

(Avşar et al., 2021) where:

- $I_{avionics}$ is the total current drawn by the avionics,
- $I_{battery}$ is the current supplied by the battery,
- t is the operational time in hours,
- c is the efficiency coefficient of the power system.

This equation is essential for determining the battery capacity required to sustain the avionics during the UAV's operation. Substituting the given values into equation (6) where:

- $I_{battery}$ =3.72AI, t=11 minutes and c=0.8

the avionics equipment is expected to draw 853 mAh from the battery during the flight.
Substituting the values into equation (1) where: I_{motor} =14,847 and $I_{avionics}$=853 mAh.
the total battery capacity is expected to draw 15 700 mAh.
To account for potential flight duration extensions and ensure safety, the battery capacity should be selected 1.25 times the calculated requirement:
$I_{battery,safe}$=15,700×1.25=19,625 mAh
The closest available battery capacity is 6S 25C 22,000 mAh Li-Po. The weight of the same batteries, including connectors, is approximately 2.5 kg.
For the designed SRUAV to perform autonomous flights, a flight computer is required. The Pixhawk Orange Cube has been selected as the most suitable flight computer, as it integrates a GPS module and various sensors, including an accelerometer, compass, gyroscope, and barometer. In addition to ensuring flight stabilization, it enables real-time data transmission and position tracking. With the GPS module included, the estimated total weight of the flight computer is 250 g.
The UAV is expected to move between trees, which are planted at 5-meter intervals, within 5 seconds. This requires a camera capable of scanning 1 meter per second at a frame rate of 13-14 FPS.
To meet this requirement with high-resolution (1080p) imaging, the ZED 2 stereo camera has been selected as the most suitable option.
In this study, the heaviest computational load falls on the mission computer. It must process high-resolution images from the camera in real-time and perform color detection. Once the target is identified, it communicates with the flight computer to stop the UAV and stabilize its position before activating the spraying system. Due to its high core count and ability to process 22 high-resolution (1080p) images per second, the Nvidia Jetson Orin AGX, shown in Figure 2, has been selected as the preferred computing platform for this study.

Figure 2. Nvidia Jetson Orin AGX.

2.2. Mechanical Design

The selected motors are capable of generating sufficient thrust with 14-inch propellers, based on the estimated weight of the UAV. These propellers, approximately 35.5 cm in length, require a wide chassis design to ensure that SRUAV operates safely without causing damage to its onboard electronic components. The chassis can be analyzed under three main sections which are body, motor arms and landing gear.
The body is constructed using two main plates, designed to integrate seamlessly with electronic components and all other parts of SRUAV. It is shaped as a 12-sided polygon, with parallel edges measuring 34 cm apart.
The upper main body houses the mission computer, flight computer, and battery, which are secured through elongated slots. Meanwhile, the lower body accommodates the landing gear and ESCs. The motor arms are positioned between these two structural components, ensuring a stable and functional design.
The motor arms must be of sufficient length to accommodate the rotors with propellers. Given that the UAV is a hexacopter, the arms are positioned at 60° angles relative to each other.
By considering the propeller length, body dimensions, and arm angles, it has been determined that each SRUAV motor arm must be at least 18.5 cm long to ensure proper clearance. Additionally, motor mounts have been designed at the ends of the arms to securely hold the motors in place.
The landing gear consists of two legs on each side, with one foot on each side for stability. The legs are designed at a 15° incline relative to the surface normal to enhance stability during landing. Due to the spraying tank mounted beneath the lower frame and the camera positioned for image acquisition, the landing gear must provide sufficient clearance. To meet this requirement, the legs are constructed from 50 cm long, 15 mm diameter carbon fiber rods. The legs and feet are connected using a T-shaped structural component, ensuring a secure and

stable attachment. Figure 3 illustrates the final design of SRUAV before the spraying mechanism is installed.

Figure 3. SRUAV.

2.3. Software Design

After assembling the mechanical structure and electronic components of SRUAV, three key software stages were eveloped which are Autonomous flight, image processing and spraying mechanism. The flowchart in Figure 4 is structured around these three main stages, outlining the overall operational framework of the UAV.

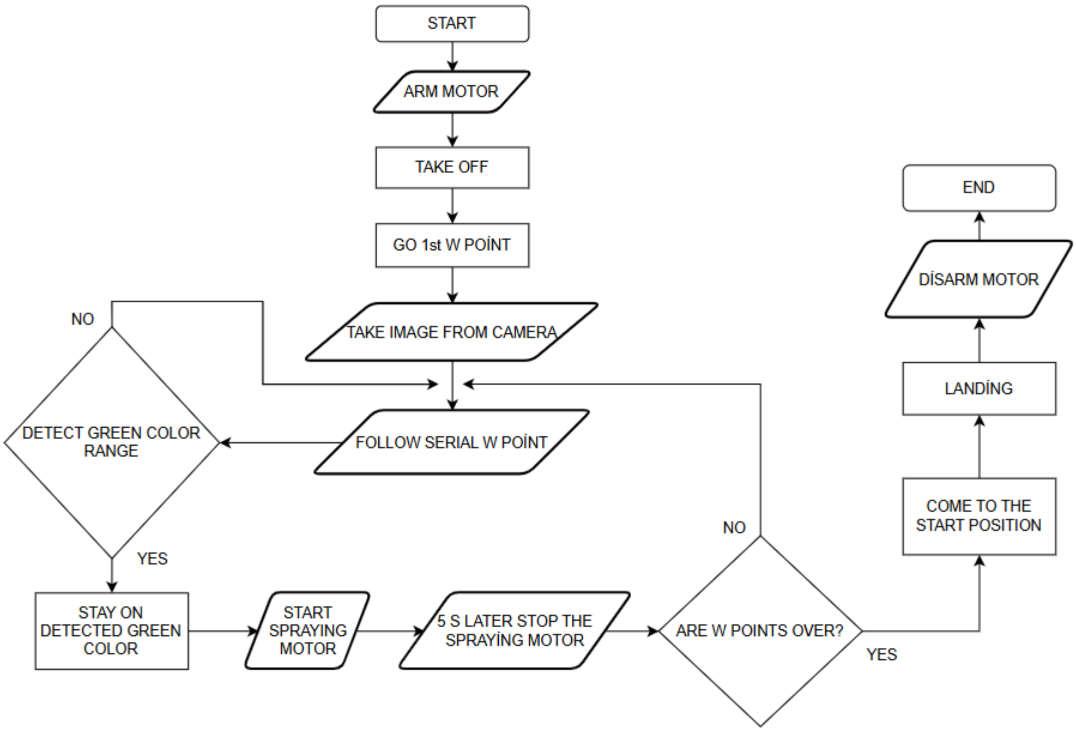


Figure 4. Spraying flow chart.

SRUAV's autonomous takeoff and landing have been executed using the Pixhawk flight controller (Gunturu et al., 2020) via the Mission Planner interface (Herlambang, 2021). After configuring SRUAV's directional adjustments (Azman et al., 2021), waypoints for the target spraying area were defined using the waypoint screen (Karasek et al., 2024).

After autonomous takeoff, SRUAV must efficiently detect trees while following waypoints, requiring a fast detection approach. Based on literature research (Abdellatif, 2008; Diwan et al., 2023), two object detection algorithms were considered which are YOLO and Color-Based Object Detection. Although YOLO is known for its high-speed object detection, implementing it for this project would require training the model on a large dataset of tree images, considering variations in shape and species (Diwan et al., 2023).

On the other hand, in the color-based object detection approach, agricultural fields are typically plowed before spraying (Anonymous, 2025), ensuring that there are no green weeds on the soil. This allows the detection of green-leaved trees using a color-based algorithm, which is faster and computationally less complex compared to deep-learning-based alternatives.

Figure 5. Working of color based object detection algorithm.

The color-based object detection algorithm is designed to identify objects within a specific color range. Given that tree leaves exhibit various shades of green, the RGB color thresholds are defined as Light green: [0,150,0] and Dark green: [80,255,80]. Objects within this color range are detected and enclosed within bounding boxes, as illustrated in Figure 5. The mission computer recognizes the enclosed objects as trees, positions the UAV accordingly, and initiates the spraying process.

3. Experimental Studies

SRUAV has undergone eight tests under various weather conditions, as summarized in Table 1. Every living organism emits a certain amount of energy under normal conditions, which appears within a specific color range on thermal imaging cameras (Tran et al, 2017). Since the sprayed trees will have leaves in contact with water, a color change is expected in thermal images (Caylı et al., 2016; Yalcıner et al., 2017).

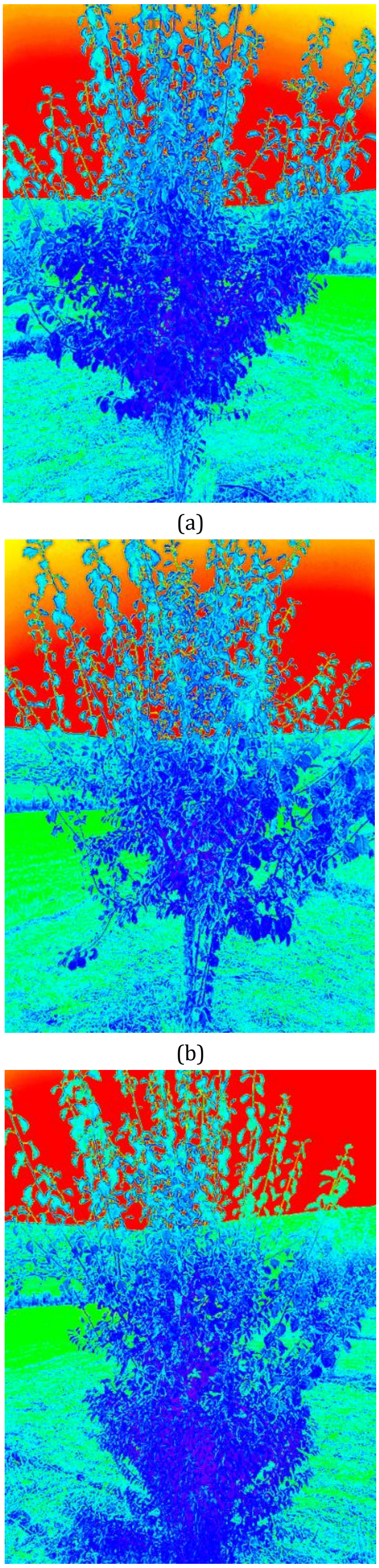
By comparing the areas that exhibit color change to the total tree surface area, the spraying success rate (or pesticide penetration percentage) can be determined.

Pairwise comparisons were analyzed to determine the effect of temperature, wind speed, and precipitation rate on spraying efficiency. In the comparison of Test 5 and Test 6, the wind speed and precipitation rate are similar, but the temperature is different. The spraying success rate shows insignificant change, indicating that the temperature has little effect on pesticide penetration. In the comparison of Test 2 and Test 3, the wind speed and temperature are similar, but the precipitation rate is different. The spraying success rate only shows a small change, indicating that precipitation does not significantly affect pesticide penetration. In the Comparison of Test 2 and Test 4, Temperature and precipitation rate are similar, but wind speed is different. Spraying success rate decreases as wind speed increases, indicating that higher wind speeds reduce pesticide penetration. In Test 4, at the lowest wind speed conditions, the spraying success rate is 92%. In Test 7, where the wind speed is highest, the success rate drops to 19%. This confirms that higher wind speeds significantly reduce pesticide penetration.

When comparing spraying efficiency with traditional methods, tests were conducted under standard weather conditions (approximately 25°C, precipitation below 20%, and wind speed below 3 km/h). Figure 6 presents thermal images of trees sprayed with pesticide using a tractor-mounted sprayer, SRUAV and a hand-operated sprayer. The tests measured and compared whic are spraying duration, pesticide consumption, spraying efficiency rates. The results are summarized in Table 2.

Table 1. Flight test schedule

	Tempreture(°C)	Percentage of precipitation (%)	Wind speed(km/hour)	Percent pestisite penetration (%)
Test 1	13	72	16	33
Test 2	19	16	10	49
Test 3	22	75	9	53
Test 4	23	14	1.5	92
Test 5	37	4	6	61
Test 6	25	4	7	57
Test 7	18	15	19	19
Test 8	13	60	11	47



(a) (b) (c)

Figure 6. Thermal image of a tree sprayed with (a) hand pump bag sprayer, (b) thermal image of a tree sprayed with tractor, (c) thermal image of a tree sprayed with SRUAV.

The most effective spraying method in terms of coverage was the manual sprayer, achieving 97% efficiency. However, pesticide consumption was three times higher than SRUAV's and spraying duration was eight times longer than SRUAV's.
For tractor-based spraying, the efficiency rate was 92%, the same as SRUAV. Pesticide consumption was twice that of SRUAV. Spraying duration was 1.5 times longer than SRUAV's. These results demonstrate that SRUAV achieves the same efficiency as traditional tractor spraying while using significantly less pesticide and requiring less time.

Table 2. Spraying methods and results

	Amount of pesticide (ml)	Spraying time (sn)	Percentage of pesticide penetration onto the tree (%)
Manual spraying	400-450	35-40	97
Spraying with tractor	300	8,5	92
Spraying with SRUAV	150	5	92

4. Discussion and Conclusion

This paper addresses spraying, one of the key aspects of precision agriculture, in response to the challenges posed by increasing population and declining arable land. To enhance efficiency and reduce waste during spraying, a six-rotor UAV has been designed.
Tests conducted with SRUAV under various weather conditions have demonstrated that wind speed plays a crucial role in spraying efficiency.
In tests conducted under similar weather conditions, SRUAV's spraying performance was compared with traditional methods.
When compared to tractor-based spraying, it provides savings with the same efficiency rate (92%) but 50% less pesticide consumption and 35% shorter spraying time. When compared to manual (hand pump) spraying, manual spraying has a higher efficiency rate (97%) but three times more pesticide consumption and eight times longer spraying time.
Excessive pesticide application in agricultural fields can cause more long-term damage than benefits (Kaur et al., 2024). In addition, manual spraying requires significant labor input over long periods of time and creates great difficulties for farmers.
All three methods have their own costs (table 3). When it comes to spraying 10 acres of land in one day:
4 workers are required for hand pump spraying and each one works for 1500 TL per day. In other words, the total cost is 6000 TL excluding the use of pesticide and water.
When we consider spraying with a tractor, one worker works for 1500 TL per day. In addition, there is approximately 500 TL of diesel consumed by the tractor.
The UAV can spray one acre in a single sortie. In other words, it needs to charge its battery 10 times. A 21,000 mah battery corresponds to approximately 0.25 kWh. 10 charges are 2.5 kWh in total. The current cost of 1 kWh is

approximately 2,12 TL, in other words, the total cost of the UAV is 5,3 TL.

Table 3. Method cost

	Diesel (TL)	Worker cost (TL)	Electricity cost (TL)
Manual spraying	0	4*1500	0
Spraying with tractor	500	1500	0
Spraying with SRUAV	0	0	5.3

To increase the spraying success rate in UAV-based pesticide application, equipping SRUAV with wind speed and direction sensors could allow it to calibrate itself based on wind conditions before initiating spraying. This adjustment would help mitigate the negative impact of adverse weather conditions and potentially improve spraying efficiency. This aspect holds significant importance for future studies.

In the image processing stage, if disease detection or health assessment of tree leaves can be performed, spraying can be targeted only to the trees that require treatment. Additionally, the amount of pesticide applied can be adjusted accordingly. This approach would help prevent excessive pesticide use, promoting more efficient and sustainable agricultural practices.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	A.F.T.	B.E.D.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there are no conflict of interest.

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Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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