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Development of an Indoor Testing Facility to Standardise the Analysis of UAV Spraying Efficacy

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ABSTRACT

Workforce shortages, growing input prices, and shortcomings in pesticide usage have caused increasing challenges to the rising production of rice in Southeast Asia. Traditional knapsack and mist-blower spraying techniques are laborious, present dangers to workers, and lead to decreased field capacity with irregular pesticide deposition. As Unmanned Aerial Vehicles provide enhanced operating efficiency and accuracy (UAVs), it is now recognised as an acceptable choice. Nevertheless, UAV spraying possesses distinct aerodynamic challenges, which include rotor-induced downwash airflow, droplet drift, and irregular deposition patterns. Such challenges are not well-addressed by the present testing approaches. The present wind tunnel facilities and computational models were mainly developed for aircraft that are manned at high altitude. Henceforth, this article stresses producing a testing facility that can be operated indoors, particularly intended to assess the performance of UAVs spraying within typical and replicable settings. The facility allows for meticulous monitoring of downwash airflow, droplet formation, and deposition distribution, which offer valuable insights into spray patterns affected by UAV design, payload, flight speed, and nozzle configurations. To ensure that the experiments are repeatable, standard operating procedures were created. Earlier tests showed that the facility can recreate real-like conditions for UAV spraying and allows for systematic adjustments of varied settings.

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The testing setup signifies a new benchmark procedure for studying UAV pesticide application. This facility not only presents a way to make spraying safer and more effective, but also supports ecologically sustainable practices in rice agriculture.

Keywords: Downwash airflow measurement, droplet distribution, indoor testing facility, spray deposition analysis, unmanned aerial vehicle (UAV) spraying

INTRODUCTION

Even though rice production frequently does not keep up with its consumption, rice continues to be the main staple food in Asia. In Malaysia, the demand for rice rose from 2.7 million metric tonnes in 2016 to an expected 3.2 million metric tonnes by 2027. Simultaneously, the amount of rice produced rose a little, from 1.75 to 1.9 million metric tonnes (Omar et al., 2019). The nation relies greatly on imported rice, mostly from Vietnam and Thailand, and it is about 70% self-sufficient. The growing disparity shows the need to improve the industry via mechanisation. Thus, the Eleventh Malaysia Plan (11MP) and Third and Fourth National Agricultural Policies (NAP3, NAP4) are among national plans that highlight this as a priority (Dardak, 2015).

Even though there is a considerable mechanisation in preparing the land and harvesting rice, the use of pesticides is still one of the least mechanised phases in cultivating rice. Although more than 90% of spraying is conducted with machines, the index of mechanisation is just 19.3%. This reveals that we still rely a lot on manual work (Muazu et al., 2014; Omar et al., 2019). Spraying is usually carried out with knapsack sprayers or mist blowers that are strenuous on the body, make workers exposed to dangerous chemicals, and do not provide good coverage. Field checks found that a large number of operators do not follow the right spraying amount and timing. This leads to inconsistent use of pesticides, less effectiveness, and more chemical waste (Ismail et al., 2019; Mairghany et al., 2018). This lack of efficiency results in cost increase, resistant pests, and health deterioration in both humans and the environment.

Unmanned Aerial Vehicles (UAVs) have emerged as an alternative technology for spraying. UAVs can operate in the fields without soil compaction, apply chemicals precisely and reduce operator exposure to pesticides. Studies report that the field capacities of using UAVs are 2.0-4.5 ha h^{-1} at application rates of 14-39 L ha^{-1} and outperforming knapsack sprayers (Giles & Billing, 2014). The adoption of UAVs has expanded to Malaysia's major rice schemes since 2018, due to its benefits, including higher efficiency and reduced labour demand (Faiçal et al., 2017; Morley et al., 2017).

Although the usage of UAVs brings many benefits, UAV spraying introduces new challenges. Rotor-induced downwash strongly affects droplet atomisation and transport. Fine droplets (<150 µm) are prone to drift, while coarse droplets limit canopy penetration

(Lan et al., 2017; Vernay et al., 2016). Non-uniform deposition across swaths has been widely reported in rice and citrus trials (Qin et al., 2016; Wang et al., 2017; Zhang et al., 2016), undermining pest control and increasing off-target risks (Kruger et al., 2019). The way rotor airflow works, along with varied payloads and flight conditions, makes spray dynamics complicated, rendering challenging optimisation.

Efforts to make simulations of UAV spraying have depended on computational fluid dynamics (CFD) and modifications of manned aircraft spray models like AGDISP (Agricultural Dispersal) and FSCBG (Forest Service Cramer Barry Grim). While CFD can visualise airflow and droplet interactions (Yang et al., 2018; Zheng et al., 2018), its accuracy depends on empirical validation. Legacy models, however, were developed for high-altitude fixed-wing aircraft and cannot fully represent low-altitude, multi-rotor UAV conditions (Teske & Barry, 1993; Yang et al., 2017). Experimental efforts using pitot tubes, anemometers, and strain gauges (Chen et al., 2017; Huang et al., 2018; Wu et al., 2019) provide insights but are fragmented, costly, and lack standardisation. Most focus on airflow measurement alone, with little integration of droplet deposition analysis.

Existing wind tunnel facilities, designed for manned aircraft, also fall short for UAV applications. They are unable to replicate the simultaneous vertical downwash and forward propulsion of UAVs when delineating droplet spectra at elevated horizontal airspeeds. Field experiments are crucial yet limited by unforeseen environmental changes. Thus, the optimisation of UAV spraying, which involves factors like flight altitude, velocity, nozzle type, and formulation, remains predominantly empirical, platform-dependent, and challenging to standardise. A controlled indoor testing facility can address these shortcomings by offering consistent and reproducible settings for UAV spraying studies. This would enable systematic assessment of downwash airflow, droplet dimensions, and deposition patterns under varied parameters. Significantly, it would facilitate the development of UAV-specific spray compositions and technologies aimed at reducing drift (de Oliveira et al., 2015; Wang et al., 2018).

This study presents the development of a dedicated indoor testing facility for evaluating UAV spraying in rice cultivation. The facility simulates field-relevant operating conditions within a controlled environment, allowing experiments to be conducted in a consistent and repeatable manner while enabling reliable measurement of results. To ensure consistency during testing, standard operating procedures were established, and systems for airflow and droplet measurement were incorporated for performance evaluation. Overall, the facility offers a controlled and configurable framework for investigating UAV spray behaviour under defined conditions and can provide a foundation for more systematic analysis of UAV spraying performance and contributes towards improving the efficiency and sustainability of UAV-based applications in rice cultivation.

METHODOLOGY

General Concept of the Development

The indoor testing facility was built in the Faculty of Engineering, Universiti Putra Malaysia. The functional floor area was roughly 23 m X 15 m, with a total ceiling height of 5 m, as shown in Figure 1. Internal partition walls were built to a height of 3 m to establish a confined testing area. The height was the maximum permitted in accordance with the present building structure. Even though the upper section of the area is left unobstructed, this arrangement permitted sufficient flow of air following every spraying session. This reduced the likelihood of excessive moisture accumulation or residual chemical concentration. This open upper clearance also served as a safety measure to avoid prolonged retention of pesticide atomisers. Access to the testing area was provided through two doors, which remained closed during experimental runs. All rig operations were monitored and controlled from an adjacent room separated by a shutter door, allowing tests to be conducted without exposing personnel to sprayed chemicals.

The indoor UAV testing facility was developed to evaluate the airflow profile of the UAV and to quantify the spraying deposition under controlled conditions, while allowing simulation of selected operational parameters observed in field applications. To get the same airflow profile and deposition effects as in the field, the facility was developed to emulate the actual operation conditions of the tested UAV in the field. An indoor facility was chosen to allow better control of the travelling operation of the tested UAV and, at the same time, to overcome the environmental disturbances that may affect the UAV spray deposition during the operation. The achieved overall length and height of the tested UAV were approximately 23 m and 4.5 m, respectively. The schematic diagram of the facility is shown in Figure 2.

The testing facility has two main sections. The first section consists of a rail support structure and its driving unit. Attached to the beam of the rail support structure was a moving carriage that was used to mount the tested UAV. The height of the mounting frame could be adjusted at three tested height levels, while the forward speed of the moving carriage can be regulated at three levels of flight speed. The required test flight heights and speeds were set accordingly before the evaluation test. The frame structure was used to secure the tested UAV onto the moving carriage.

The second section was a sampling platform structure and its adjusting height unit to cover the total sampling area for spray deposition. The sampling platform was constructed to have a total of 49 sampling points, and at each of these points, a sample holder stand was placed for holding a pressure sensor or water-sensitive paper in accordance with the mode of the test runs conducted.

This facility was also equipped with the respective measurement sensors to measure the downwash pressure produced by UAV rotational blades, speed of the carriage, ambient air,

Figure 1. Indoor laboratory layout

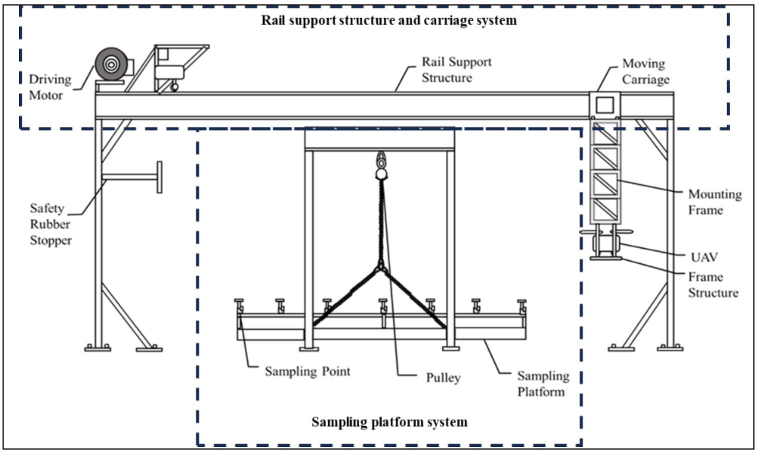


Figure 2. Schematic diagram of the indoor UAV testing facility showing (i) rail support and carriage system and (ii) sampling platform system

ambient humidity, and temperature of the test area. All of these measuring sensors were interfaced with a dedicated data acquisition system that could receive the measured signals in real time, control the information, display the information on a monitor screen and finally record the information into a storage medium.

Rail Support Structure Assembly

The railing beam and its two-end column supports were built from 305 mm x 102 mm x 33 kg/m mild steel I beam sections (Figure 3(a)). Attached to the beam was the moving carriage that was used to carry the tested UAV (Figure 3(b)). The moving carriage driving unit was driven by a 3-phase induction motor, brand TECO (model: AEEBAN) with a power size of 5.5kW. A pulley used to lift and hold the UAV during set-up was installed below the driving unit.

The maximum designed weight limit for moving carriage was 100 kg, and the unit could travel forward or reverse condition on rollers within an enclosed frame on the railing beam. The forward speed of the moving carriage was designed to be regulated up to the maximum linear speed of 10 m/s. This could be done by setting the required speed at the control console of the main driving unit. The moving carriage was used to hold the UAV and its mounting frame at a height of 3.5 m from the ground (Figure 3(c)). Changes to the height of the UAV from the ground could be adjusted by attaching the relevant mounting frame that could allow the carriage to hold the UAV at 1.5 m and 2.5 m from the ground (Figure 3 (d)). These three parameters of height and speed of the carriage would need to be set accordingly before the test evaluations were performed on the UAV.

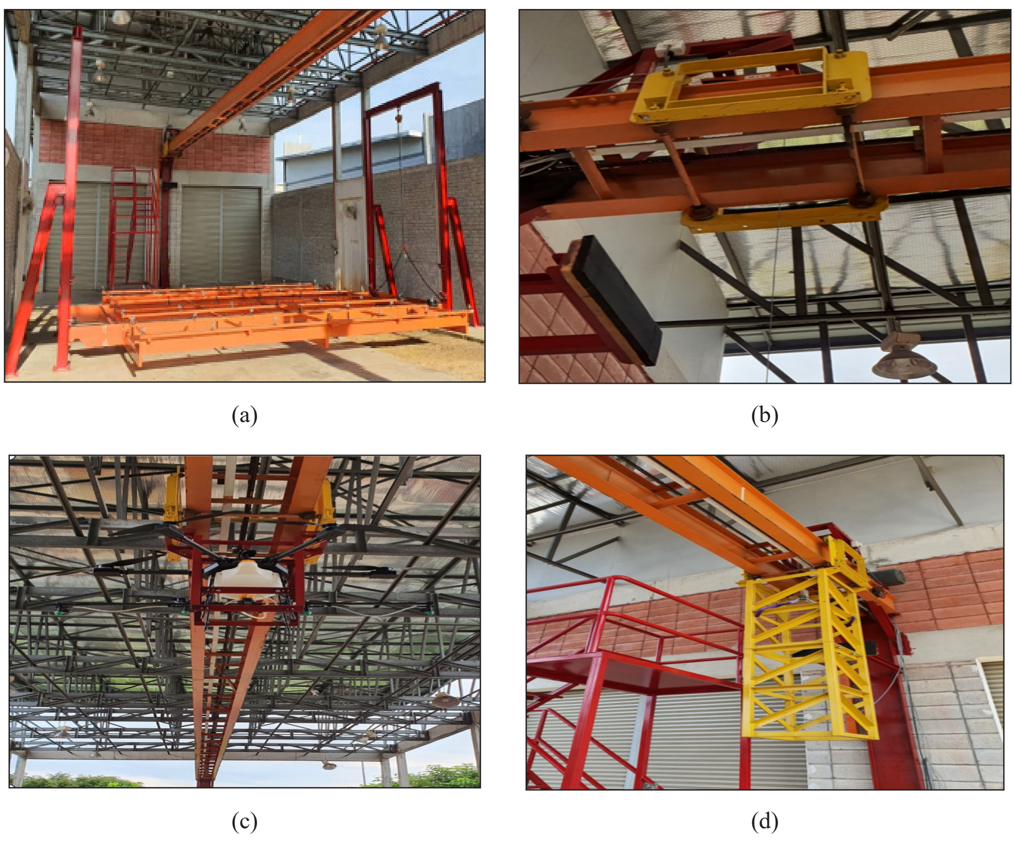


Figure 3. UAV testing facility main components: (a) rail support structure and sampling platform; (b) moving carriage at the highest level; (c) UAV mounted on moving carriage at the highest level; (d) moving carriage at the lowest level

Sampling Platform Structure Assembly

The sampling platform structure with a total sampling area of 6 m X 6 m was built from rectangular hollow steel located underneath the railing support structure. The entire sampling area was equipped with an adjustable lifting pulley at both sides that could raise the entire sampling platform up to a maximum of 3 m at 0.5 m increments. The sampling area was constructed with a total of 49 sampling points, where the location of the points could be adjusted to 1 m X 1 m (Figure 4(a)) or, 0.5 m X 0.5 m (Figure 4(b)) grid coordinates in accordance with the spray boom size of the UAV tested. The sampling holder stands were specifically made to fit the pressure transducer (Figure 5(a)) or the water-sensitive paper in their respective tests (Figure 5(b)). Each sampling holder stand could be rotated and adjusted accordingly to meet the desired setting.

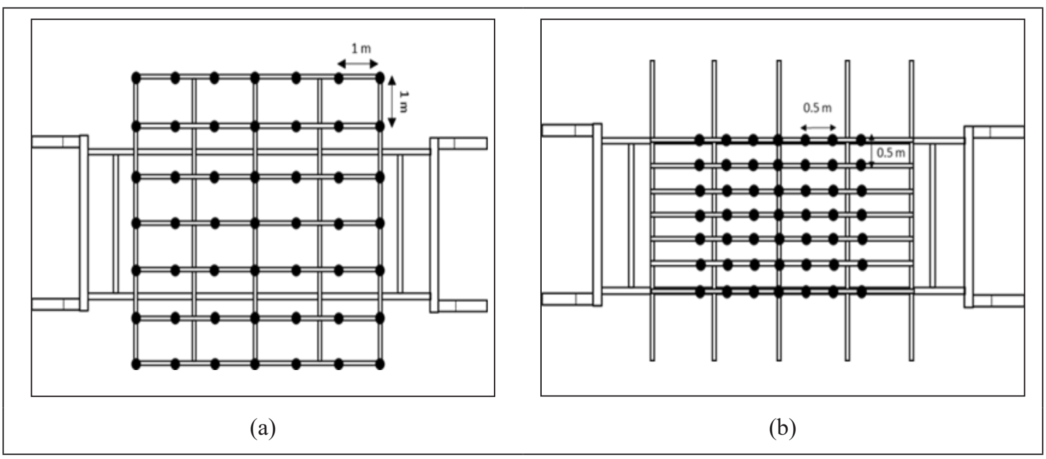


Figure 4. Sampling platform arrangement at (a) 1 m X 1 m grid and (b) 0.5 m X 0.5 m grid

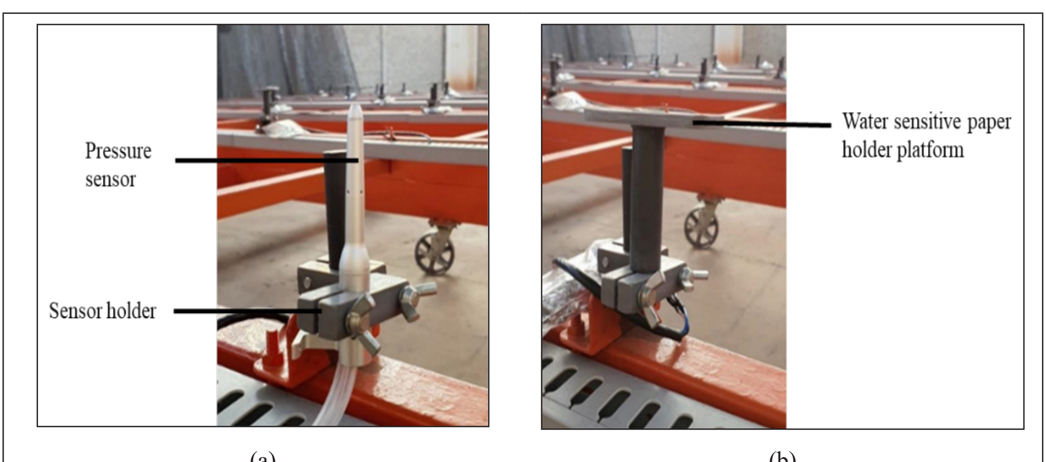


Figure 5. (a) Pressure sensor and (b) water-sensitive paper platform fixed at the sampling point

Data Acquisition System (DAQ)

Measuring Sensors

Forty-nine PT60 - MPXV7002 differential pressure transducers were fixed at every 49 standpoints on the sampling platform before the test commenced. The transducers were used to measure the downwash pressure produced by the UAV's rotating blades. It allows the measurement of the pressure of -2 to 2 kPa (-0.3 - 0.3 psi) through each port for pressure sensing and vacuum sensing, and has 0.5 to 4.5 V Output. The transducers were connected to the DAQ and recorded the differential pressure of the downwash during the test runs.

One inductive proximity encoder was installed at the main drive shaft and used in the triggering process. The encoder counts the rotation of the drive shaft as the carriage moves forward. The triggering started at the 10th rotation. Once triggered, all the pressure transducers began taking data and stopped when triggered again when the carriage was at the 21st rotation. In the interfacing software, the user would be able to set at which rotation the proximity encoder would start and stop to trigger the pressure sensors. Four pulse signal wind sensor digital anemometers, four units of LM35 temperature sensors and four units of HPP809A031-ND humidity sensors that were located at four different locations in the indoor facility were used to measure the ambient wind, temperature and humidity of the laboratory space. The height of all the transducers was 2 m from the ground and had a distance of 0.7 m from the wall. The readings from the four sensors were sent to the DAQ data acquisition to be recorded.

DAQ Hardware and Software Systems

The data acquisition system (DAQ) for acquiring data comprises the following: (i) transducers for acquiring the measured data, (ii) DAQ hardware for interfacing the sensors to a computer, (iii) computer, (iv) DAQ device drivers, and (v) DAQ software to process, visualise, and store the measurement data. The block diagram of the data acquisition system with associated transducers is shown in Figure 6.

The DAQ hardware and software systems are comprised of two main components. One unit of National Instrument (NI) cRIO- 9073 controller, 5 units of NI- 9205, one unit of NI-9422, one unit of NI-9411 modules, and one unit of desktop computer were used as hardware to acquire data from all the transducers. The modules were selected to fulfil their compatibility with the available transducers. All data processing from the signal acquired was done on the computer.

The NI-DAQmx driver from the National Instruments was installed on the desktop for communications to be made to all available devices in the system. Laboratory Virtual Instrument Engineering Workbench (LabVIEW) 2019 from the National Instruments was used as a system-design platform and development environment for developing the visual programme for data monitoring and acquisition.

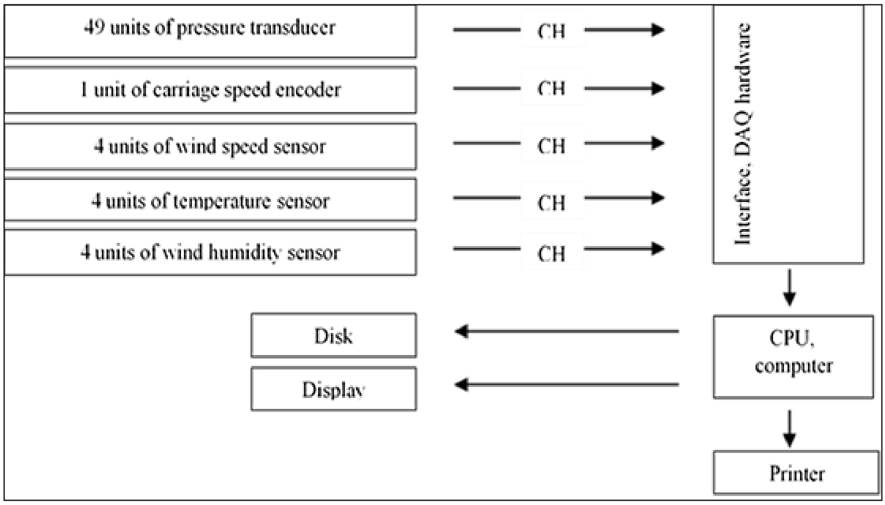


Figure 6. Block diagram of a data acquisition system (DAQ)

The display of data was made available to the user in real time on the monitor screen, and the data was permanently stored in a defined file in the storage medium of the computer. Once the data has been recorded in the designated files, it is readily extractable for further analysis. The types of data that were recorded were i) ambient data from all temperature, humidity and wind speed sensors, ii) average values of the temperature, humidity and wind speed sensors, iii) carriage speed, and lastly iv) data captured by pressure sensors.

Determining the Sampling Area

The sampling area was the area where the speed of the carriage would remain stable at the rated speed set by the user. The sampling area is important to be determined as a guideline to allocate the pressure sensors for the downwash data and water-sensitive paper for deposition verifications while the UAV is stable at the rated speed. The sampling area was defined as the section of the rig where the carriage maintained a stable velocity, ensuring accurate placement of pressure sensors and water-sensitive papers for downwash and deposition measurements. Stability of speed was crucial for reliable and repeatable experiments.

To determine the sampling area, the carriage movement was calibrated along the rail. Every sprocket turn was marked on the floor, with 27 stops reported (S1-S27). Speed was measured at various set speeds (2-7 m/s), making use of data from an inductive proximity encoder and timing software. This helped the plotting of the velocity profile over the distance travelled, allowing the determination of the areas where the motion was constant. The sampling area was determined by analysing the carriage speed profile along the rail system to identify regions of stable motion suitable for measurement.

Development of Testing Rig SOP

An SOP was developed for facility usage to allow consistent adherence to technical requirements and to support data quality. The SOP's developed for the testing procedure are described below.

Selection of UAV

Any UAV that is commonly used for aerial chemical spraying in wetland rice cultivation could be selected to undergo the test. As the UAV configurations are different from each other, before the test, the UAV used in this study needs to be measured for the purpose of building the mounting frame. Figure 7 shows an example of the UAV tested and the mounting frame built to mount the test UAV on the carriage.

Figure 7. UAV is placed in a custom-designed mounting frame before mounting onto the testing rig

Setting the Height, Speed, and Location of the Moving Carriage

The height and speed of the moving carriage of the rail support structure need to be set before executing the spraying evaluation by the tested UAV. Adjustments to the height of the moving carriage can be 1.5 m, 2.5 m, or 3.5 m from the ground. To perform the tests, a carriage mounting frame extender (Figure 8(a)) was used to hang the tested UAV to achieve the required heights from the ground (Figure 8(b)). The moving speed of the carriage could be set to a maximum speed of 10 m/s by setting the frequency at the Shihlin AC driver parameters (Shihlin Electric, SF-G Series AC Drive). Based on the available parameters, three different speeds (i.e., low, medium, and high) were set. In addition, the moving carriage had to be in the middle of the sampling area for the spraying or downwash evaluation under hovering conditions. For the evaluation of spraying under moving conditions, the moving carriage with the mounted UAV was set to move from the starting point location until the endpoint of the railing beam.

(a) (b)

Figure 8. (a) A carriage extender used to create the height of the UAV; (b) Extenders 1 and 2 were used to create heights of 2.5 m and 1.5 m from the ground, respectively

Deciding the Area of the Sampling Point

The sampling point area had to be determined according to the spray boom size of the tested UAV. As such, the evaluation of the sampling points on the sampling platform structure was determined by fixing them at grids of 0.5 m X 0.5 m and 1 m X 1 m sampling points.

Deciding the Type of Evaluation

The indoor testing facility allows two main forms of assessment to be conducted. The first involves characterising the rotor-induced downwash using pitot tube sensors positioned at the designated grid points on the sampling platform. The second involves evaluating spray deposition, in which water-sensitive papers are placed at the same grid locations to capture droplet distribution from the UAV sprayer boom. When switching from airflow measurement to droplet deposition testing, the pressure sensors on the platform are removed and replaced with water-sensitive papers to ensure full coverage of the sampling grid.

Setting the Rotational Speed of the Blades

This was used to obtain accurate downwash and deposition data of the UAV using the developed testing facility; the UAV's blade rotational speed was set to be like the rotational speed of the UAV blades during actual field flight operation. To do so, a field test was carried out beforehand to obtain the rotational speed data of each UAV blade.

In this field test, the rotational speed of each blade on the UAV was recorded under various conditions of different payloads and flight speeds. After the field test, these recorded rotational speeds were accessed from the UAV flight controller console using the interfacing software. The rotational speed data was used as a reference in setting up the rotational speed of the individual blades during the evaluation test in the indoor testing facility. However, while the system allows consistent setting of rotational speed under defined payload and carriage movement conditions, detailed quantitative monitoring of rotor speed fluctuations during operation was not conducted in this study.

Based on the test that had been done using the testing rig, there are two methods in setting up the rotational speed of the blades to emulate the actual rotational speeds in the field. The first method was executed on Advansia UAV (A1) by bypassing the flight controller and instead connecting to the ESC of each motor directly to the receiver and external power source. In this study, 2 motors were connected to the servo channels of one receiver, where one transmitter controlled the speed of two motors. Thus, for the hexacopter, 3 transmitters were used. Throughout the tests, the spray pump connection has stayed connected to the flight controller and was activated or stopped using the UAV controller shown in Figure 9.

To set the speed of the blade at different combinations of flight speeds and payloads, the data collected from the field was taken as a guideline to determine the test variables. While setting the speed of the blade using a transmitter, the rotational speed of the blade could be checked or revised using a wireless tachometer that was fixed near the blade. The wireless tachometer of the Arduino IR sensor can read at a maximum of 10,000 rpm, and it is located close to the rotating motor. The reading from the sensor was sent to the receiver at every 0.5 s via radio frequency (RF), which has a limitation of 50 m distance of coverage. The receiver, on the other hand, was connected to the computer via a USB port, so that the reading of the sent rotational speed by the sensor was displayed in the computer using the Arduino IDE software (serial monitor). The process of receiving and setting the rotational speed of the blades is shown in Figure 10.

Another method of setting the rotational speed was executed on UAV Oryctes by Poladrone. The same procedure in collecting actual rotational speeds from the field was carried out with different combinations of payloads and flight speeds before the rotational speed setting process of the UAV blades and was later uploaded to the rotational speed setting system. The rotational speed setting process for this method was done by bypassing the flight controller and was instead controlled by the Raspberry Pi 3 B+. Raspberry Pi is a series of small single-board computers that are widely used in robotic and other computing projects. Python was used as the programming language. The Raspberry card was assembled on the UAV and remotely accessed by VNC® Connect software from a Windows PC via the wireless local area network (WLAN) shown in Figure 11.

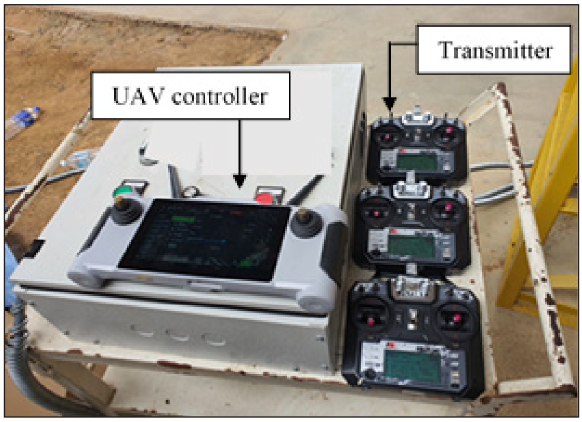


Figure 9. 3 Transmitter were used to regulate the rotational speeds of the 6 blades and 1 UAV controller to activate/stop the spray pump

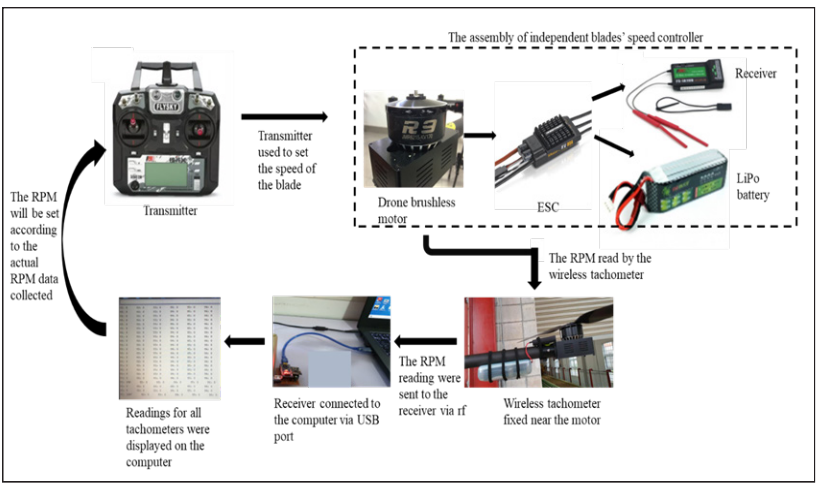


Figure 10. The process of receiving and setting the rotational speed of the blades

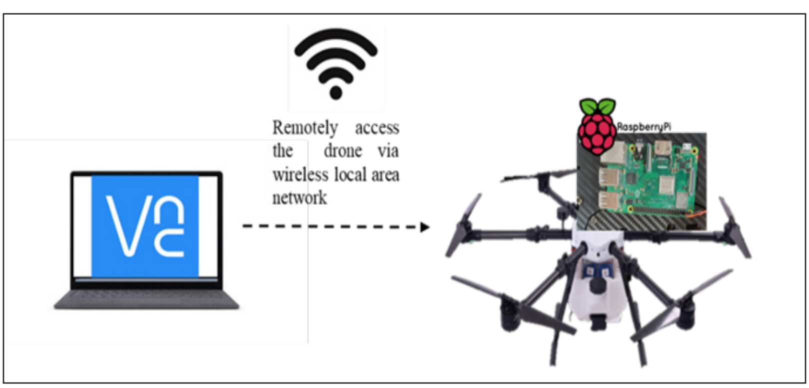


Figure 11. VNC viewer was used in remote communication with the Raspberry Pi card via WLAN

Acquiring Downwash Flow Field

The downwash airflow was assessed under two operating conditions: hovering and forward motion. During the hovering tests, the UAV was positioned at a specified height in the centre of the sampling area, and its rotor speed was set according to the selected operating parameter. The pressure sensors installed across the platform were used to record the resulting downwash. To generate a full three-dimensional profile of the pressure distribution, the measurements were repeated at several platform heights.

For the forward-motion condition, the blade rotational speed was adjusted to correspond with the intended flight velocity and payload. The vertical position and travelling speed of the carriage were then set to match these operating parameters. While the UAV traversed the rail system, the pressure sensors kept taking readings of the downwash, and these readings were being recorded at the same time via the data collection unit. The process was repeated at various platform height points to achieve the 3D pressure field during forward motion. MATLAB was later used to analyse and visualise all gathered pressure data (The MathWorks, Inc.).

Verifying the Droplet Deposition

To measure the distribution of droplet deposition, water-sensitive papers were fixed at sampling points on the sampling platform. The application parameters, such as blade rotational speed, height and speed of the carriage, were to be adjusted according to parameters determined in previous sections. The UAV spray tank was filled with the spray chemicals, and the spray system was set to run for at least 5 s in a stagnant position before the start of the test to ensure that the flow was stable. All water-sensitive papers were collected immediately upon the completion of the UAV test run. Each of the collected water-sensitive papers was scanned using an EPSON L360 scanner. The images were saved at a resolution of 8-bit, 600dpi as TIF. image format. The saved images were then further analysed using the DepositScan droplet deposition imaging system (USDA, USA) (Zhu et al., 2011). The deposition that was gathered from this test included a spatial droplet deposition pattern.

Loading and Unloading Pesticides

Spray chemicals were pre-filled into the spray tank earlier, while the UAV was still on the floor and were refilled while the UAV was hung on the rig using the stairs provided. For better accuracy of results, the remaining spray chemical in the tank was flushed before replacing it with another spray chemical.

Safety Precautions

Safety precautions implemented during the experimental procedures are summarised in Table 1.

Table 1
Safety precautions implemented during UAV spraying experiments

No.	Safety Aspect	Description
1	Handling of chemicals	All pesticide handling, loading, and disposal were carried out in accordance with manufacturer and regulatory guidelines
2	Equipment cleaning	Spraying equipment was cleaned before each test, and neutralising agents were applied when necessary
3	Personnel briefing	All personnel were briefed on test procedures before the operation
4	Restricted access	Personnel were kept clear of the UAV operation and spraying area during testing
5	Personal protective equipment (PPE)	Appropriate PPE was worn to minimise chemical exposure
6	Exposure awareness	Potential exposure routes (inhalation, ingestion, and dermal contact) were identified and controlled

Preparing Report

The test report was prepared to include detail documentation on the technical specification of the test UAV and related picture or technical drawing of the test UAV, spraying application parameters (i.e. flight height and flight speed), spray system technical specifications (i.e., spray pressure, flow rate, application rate, nozzle type, nozzle distance, and the number of nozzle), spraying material specifications (i.e., temperature of spraying materials and its physical properties), ambient conditions (i.e., air temperature, relative humidity and ambient air) and the details results from the evaluation. From the environmental data collected, the ambient temperature, wind and humidity of the laboratory space between 7 a.m. and 10 a.m. were recorded to be at around 24-28 ^{o}C, 0-0.83 m/s of ambient wind and around 44 %- 57% of humidity.

RESULTS AND DISCUSSION

Carriage Motion Stability and Sampling Area

The stability of carriage motion is a critical factor in ensuring reliable measurement of both downwash and droplet deposition. Stable speed regions were identified between S8–S20, with the most suitable sampling zone located between S11-S19. This ensured that sensors and water-sensitive papers were positioned within a region of uniform carriage velocity, thereby improving the consistency of experimental measurement. Figure 12 illustrates the final location of the sampling platform, selected based on overlapping stable regions across multiple test speeds.

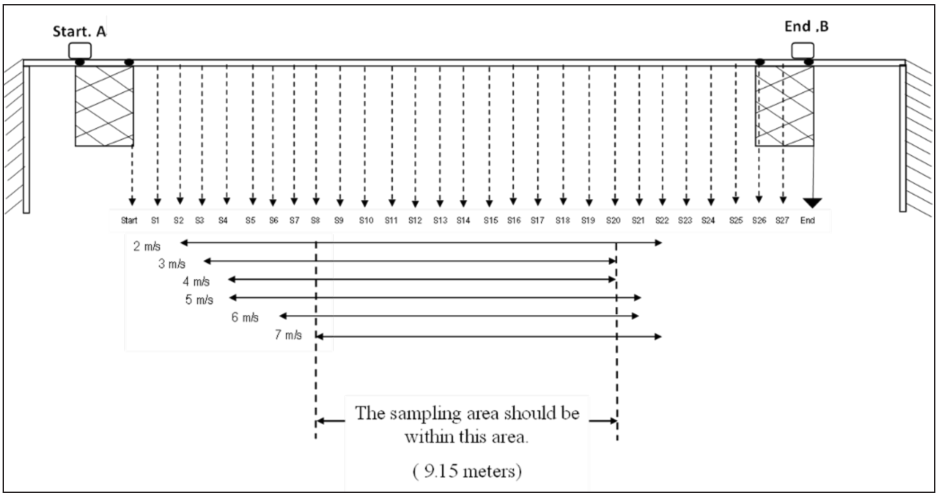


Figure 12. The location of the sampling area

Facility Performance and Downwash Measurement

The indoor testing facility was developed to provide a stable and repeatable environment for examining UAV spraying behaviour. Although the wall height was restricted to 3 m, preliminary observations indicated that this level of containment was sufficient to suppress unwanted air circulation and allow the spray cloud to settle before reaching the sampling grid. The adjustable flight height, carriage travel speed, and rotor speed controls enabled the UAV to be operated in conditions that approximate typical field spraying while maintaining experimental control.

Compared to wind tunnel-based methods, a more representative approach for analysing rotor-induced downwash effects on spraying in real situations is provided by this facility. Wind tunnel research usually keeps the UAV still or hovering (Grant et al., 2022; Wen et al., 2019; Yang et al., 2018). This can make it hard to see how the rotor's airflow interacts with the spray during actual forward movement. Likewise, tests performed at a set blade RPM (Wu et al., 2019) provide valuable aerodynamic data but fail to represent the ongoing changes that happen during real spraying. The existing facility overcomes these constraints by enabling regulated movement and configurable settings, which means the spray deposition patterns it creates more closely match what occurs in practical spraying conditions.

The facility was built to assess UAV downwash airflow and droplet deposition within a single experimental framework. However, while droplet deposition measurements were successfully demonstrated, the downwash pressure measurement subsystem did not produce a complete dataset due to intermittent sensor noise and signal instability. Nonetheless, the experimental configuration and data collection framework were completely developed.

The absence of comprehensive airflow information does not indicate a design defect but rather a hardware restriction. As a result, future optimisation efforts should emphasise sensor calibration and electrical shielding to enhance the reliability of the measurements. It is hoped that this subsystem is expected to provide quantitative datasets for the validation of computational fluid dynamics (CFD) simulations.

Droplet Deposition Characteristics

Verification of droplet deposition using water-sensitive papers revealed consistent spatial patterns across the sampling area. A higher droplet density was observed beneath the UAV centreline, with a gradual reduction towards the outer regions. This pattern matches what was documented in past studies about how UAV rotors create downwash during spraying (Lan et al., 2017; Wu et al., 2019). The ability of the facility to capture distinct and repeatable deposition patterns demonstrates its effectiveness as a controlled platform for analysing spray distribution under defined operating conditions.

The table of droplet deposition shown below (Table 2) represents deposition data collected using this testing rig. The selected flight heights and carriage speeds were chosen to represent typical operating conditions observed in UAV-based spraying and allow spray behaviour to be evaluated under controlled settings. Although the dataset is intended as a preliminary demonstration rather than a full validation, it shows that the facility can produce consistent and interpretable deposition data for comparison.

Table 2
Deposition image at every sampling point in a line

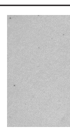
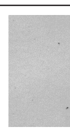
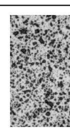
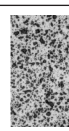
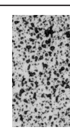
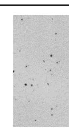
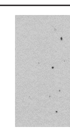
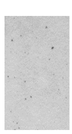
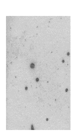
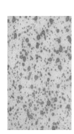
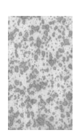
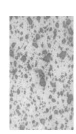
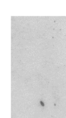
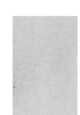
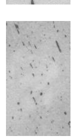
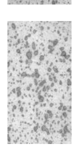
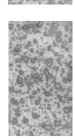
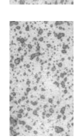
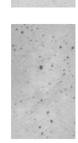
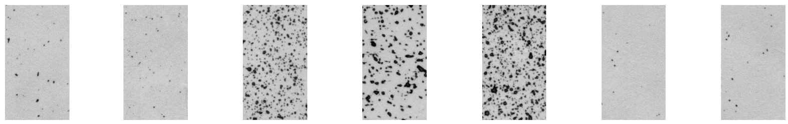
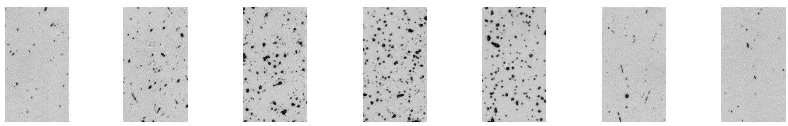
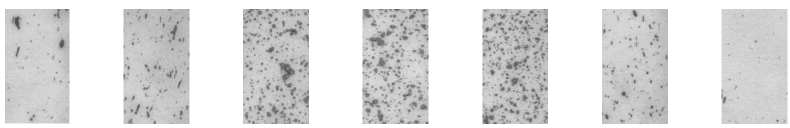
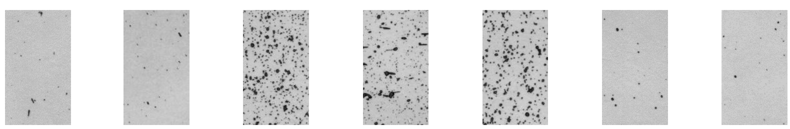
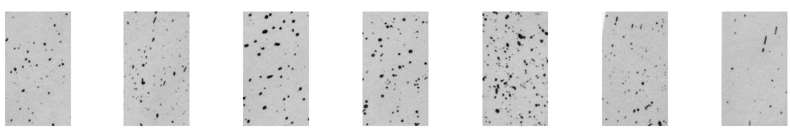
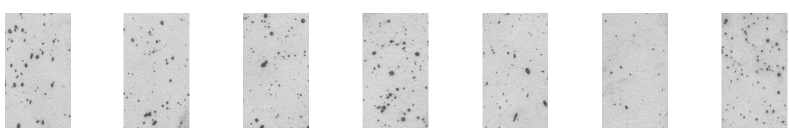
Parameter		**Deposition Image at every Sampling Point in a Line**						
Speed (m/s)	**Height (m)**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
2	1.5							
2	2.5							
2	3.5							

Table 2 (*continued*)

Parameter		**Deposition Image at every Sampling Point in a Line**						
Speed (m/s)	**Height (m)**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
4	1.5							
4	2.5							
4	3.5							
6	1.5							
6	2.5							
6	3.5							

Overall, the developed testing facility provides a structured experimental framework for investigating UAV spray behaviour under controlled conditions. Although full aerodynamic characterisation remains under development, the current system successfully demonstrates its capability for droplet deposition analysis and establishes a foundation for future studies integrating airflow measurement, spray optimisation, and drift reduction strategies.

CONCLUSION

This study presented an indoor setup for a testing facility to assess UAV spraying behaviour in a controlled and replicable setting. The setup enables modifying operational factors to observe how they impact droplet deposition. It offers a viable substitute for outdoor experiments where environmental variations may affect actual outcomes. The droplet deposition trials verified that the setup can generate consistent and clear spray patterns, demonstrating its suitability for studies that compare and optimise various methods. The downwash pressure measuring subsystem has yet to produce dependable airflow data. However, including it in the facility links aerodynamic characterisation with deposition results. The facility, hence, provides a solid base for better studies on using UAV pesticide spraying. In the future, endeavours will concentrate on making the airflow sensing system stabilise, broadening the testing settings, and integrating computational modelling to predict how well the system works. These advancements are anticipated to make UAV spraying in agricultural applications more efficient and diminish the number of pesticides that miss the target.

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