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Evaluation of Almond Harvest Dust Abatement Strategies Using an Aerial Drone Particle Monitoring System

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Abstract: This study demonstrates the feasibility of a mobile aerial drone particle monitoring system (DPMS) to measure and detect changes in harvest dust levels based on moderate adjustments to harvester settings. When compared to an earlier harvester, a new harvester operated at standard settings produced 35% fewer PM2.5s, 32% fewer PM10s, and 42% fewer TSPs. Increasing the ground speed had an adverse effect on dust mitigation, while reducing it by half only offered a slightly more favorable margin. The mutual effects of some meteorological factors were found to be slightly correlated with PM10 and TSP readings and caused significant variability in PM2.5 readings. The current findings show similar trends to PM reduction estimates of previous studies, with only a nominal difference of 10 to 15% points. Overall, the DPMS was found to perform well within an acceptable statistical confidence level. The use of DPMSs could reduce the logistical needs, complexity issues, and feedback times often experienced using the Federal Reference Method (FRM). Further investigation is needed to verify its robustness and to develop potential correlations with the FRM under different orchard location and management practices. At this stage, the current aerial DPMS should be considered a rapid screening tool not to replace the FRM, but rather to complement it in evaluating the feasibility of dust abatement strategies for the almond industry.

Keywords: San Joaquin Valley; almond harvesting; particulate pollution; drone sampling; PM2.5; PM10; TSP

Citation: Baticados, E.J.N.; Capareda, S.C. Evaluation of Almond Harvest Dust Abatement Strategies Using an Aerial Drone Particle Monitoring System. *Drones* **2023**, *7*, 519. https://doi.org/10.3390/drones7080519

Academic Editor: Pablo Rodríguez-Gonzálvez

Received: 29 May 2023
Revised: 3 August 2023
Accepted: 4 August 2023
Published: 8 August 2023

1. Introduction

The San Joaquin Valley (SJV) of California, USA is responsible for 80% of the world's almond supply, valued at 5.62 billion dollars in 2020 [1]. While the SJV is the most productive agricultural basin in the nation, it is also under continued scrutiny for its significant contribution to particulate matter (PM) pollution. Workers in almond orchards and the residents of surrounding areas are constantly exposed to an immense quantity of airborne particulates during almond harvest season. For this reason, the SJV Air Pollution Control District (SJVAPCD) required agricultural operations to reduce their PM10 (airborne particulates with $\leq$10 µm in nominal aerodynamic diameter) production via the implementation of conservation management practices (CMPs) to achieve compliance with the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS). The almond industry was able to reduce their 2003 emissions level of 4570 kg PM10/km^2 to 3500 kg PM10/km^2 via the implementation of conservation management practices and, thus, the whole district was able to reach PM10 NAAQS compliance in 2008 [2]. In 2018, the SJV was again faced with its most critical air quality challenge of compliance with fine particle (PM2.5) NAAQS. The California Air Resource Board (CARB) adopted the 2018 Valley PM2.5 Plan, which aims to demonstrate how the SJV will meet each of the federal PM2.5 standards by regulatory deadlines. Existing CARB dust mitigation strategies are projected to be insufficient to reduce PM2.5 levels as the population continues to grow [3].

Almond harvest dust levels are measured and evaluated based on the US EPA Federal Reference Method (FRM) for both non-regulatory and regulatory purposes. The FRM and the Federal Equivalent Method (FEM) require the use of specialized ground-based PM samplers deployed both upwind and downwind of the almond orchards in order to measure net mass concentrations (in μg/m^3) of particulate matter. The latter values are then used to estimate PM emission factors (in kg PM/km^2) using AERMOD inverse dispersion modelling [2,4]. In the past, PM emission studies were all conducted using the FRM protocol [5–8]. These studies reported that operational changes such as modifications in sweeping practices, separation fan speeds, and forward ground speeds have shown promise in reducing PM levels. Although FRM has been the longstanding protocol used for regulatory purposes, decades of almond emission studies have revealed that FRM methods tend to require tedious experimentation, equipment deployment, and meticulous sample handling [9].

As the almond industry continues to explore opportunities to reduce harvest dust, alternative dust measurement systems that can address the challenges faced during FRM dust mitigation studies should be considered. A number of alternative air sampling systems were previously tested in agricultural operations, such as the use of an industrial transmissometer [8] and light detection and ranging (LIDAR) technology [10]. Most recently, US EPA visual emission techniques (VEEs) were used to evaluate the effectiveness of low-dust harvesters to reduce visible dust levels [9]. These techniques provided practical information such as relative intensity of harvest dust and reduction estimates within a much shorter time frame than the FRM. However, these techniques fail to characterize the different PM cuts—PM2.5, PM10, and TSP in μg/m^3—in harvest dust, which are required for regulatory purposes. In this regard, this study presents a sampling protocol of using portable PM samplers carried by unmanned aerial vehicles (UAVs) to track and collect harvest dust during real-life nut-picking operations.

Aerial drones (or UAVs), remotely piloted aircraft systems that were originally used as military devices, have become popular in recent years because of their civil and scientific applications [11]. Various studies have utilized drone technology as part of recent air sampling systems. A 2015 study was able to demonstrate the feasibility of UAV with an attached monitoring device to collect and profile vertical PM2.5 concentrations in an urban setting [12]. More recent works involve aerial PM spatial analysis on university campuses [13,14] and in the collection and characterization of airborne particles at 10 m above the water level of some major US lakes [15]. To the best of the authors' knowledge, portable PM samplers airborne via UAV have never been used before to assess the PM levels during an almond harvest. Hence, this study aims to develop an aerial sampling protocol to follow harvest machinery in order to obtain almost real-time measurements of harvest dust concentrations. The aerial drone particle monitoring system (DPMS) was tested for its ability to detect changes in PM levels as a function of harvester's forward ground speed and fan separation speed while considering the effects of important meteorological parameters. This new mobile system to assess harvest PM levels will allow almond growers to gain immediate knowledge about the quantity of dust being produced and the extent of dust reduction due to operational changes without solely relying on FRM protocols.

2. Materials and Methods

2.1. Study Area

Two almond orchard plots adjacent to each other were selected as the study area (Figure 1). The first site was a 40-acre (161,874 m^2) plot with a total of 60 tree rows. The second site was only a portion of the adjacent plot, equivalent to 10 acres (40,469 m^2), for a total of 16 tree rows. The study area was located at the corner of Rd 84 and Ave 388, Dinuba, California. It lies between the latitudes 36°29′58.2″ to 36°29′42.02″ North and the longitudes 119°23′8.45″ to 22′52.83″ West. Each tree row was spaced 22–23 ft (6.7–7.0 m) apart and each tree was spaced 16 ft (4.88 m) apart in the same row.

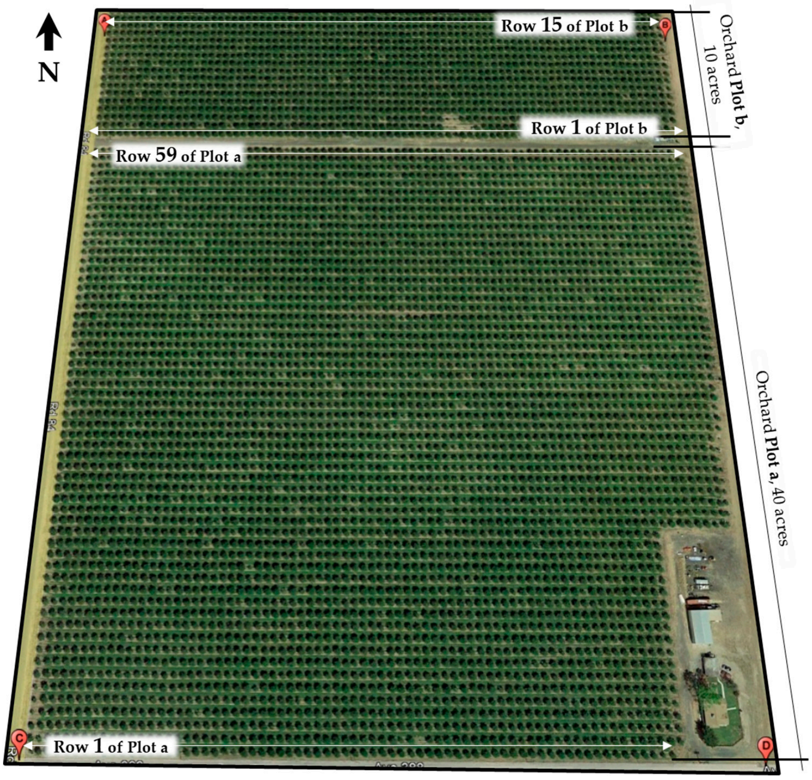


Figure 1. Almond orchard study area consisting of Plot a (59 harvested rows) and a portion of Plot b (15 harvested rows).

Local ambient meteorological data were recorded using a 7-m tall weather station (Texas Electronics, Dallas, TX, USA), deployed in an open area, 100 ft (30.48 m) southeast of the study plot. It included the following sensors: TTH-1315 temperature/humidity (accuracy $\pm$ 1.5%), SP-lite solar radiation (accuracy $\pm$ 2%), and TB-2012M barometric pressure (accuracy $\pm$ 1.3). All sensors were connected to an EWC-100 data controller/logger capable of 10-min logging intervals, powered by a 20W solar panel.

2.2. Harvester Operational Modifications

Surface dust in the study plot are consist of loose soil particles and other debris which are picked up together with the almond nuts during harvesting. As the harvester travels within the row to pick up the windrow (consisting of nuts, dust, and other debris), the nuts are simultaneously separated from the extraneous field debris. The cleaned nuts are conveyed towards the attached collection shuttle, while the larger debris is dropped back onto the ground and the dust is removed via the exhaust of the separation fan. Both the aerodynamic and mechanical removal of soil and other debris generate large dust plumes and, with appropriate wind conditions, will likely disperse and reach human settlements near the orchard.

A Self-Propelled 8770 (Salida, CA, USA) harvester was used to test the effects of varying harvester ground speed and separation fan speed (treatments) on the PM levels present in the harvest dust plumes. This machine is a CAT engine-driven model and considered a low-dust harvester, primarily due to its improved cleaning chains and variable settings for ground speed and fan flow. The control harvester was the Flory 480 (Salida, CA, USA), a tractor-towed older model, with a tractor power take-off of about 85 hp, equivalent to a standard 3 mph (1.34 m/s) harvest speed and 900 rpm fan speed. The range to which the treatment levels were varied was dictated by both the machine manufacturer and the orchard owner (Table 1). Their approval was necessary to ensure that operational changes during the tests would cause little disruption to their existing practices and keep potential efficiency losses to a minimum. Each treatment was replicated three times. There were three rows harvested for each replicate, with short break periods before starting the harvest of the next row. Codes were assigned for all treatments and used to generate a completely randomized order of daily runs which became the basis of the flight missions shown in Table 2.

Table 1. Harvester treatments and operational variables during the field tests.

Treatment ID * (A, B, C Stand for Replicates)	Ground Speed (m/s)	Fan Speed (rpm)
T1A, T1B, T1C	1.34	900
T2A, T2B, T2C	1.34	900
T3A, T3B, T3C	2.23	900
T4A, T4B, T4C	2.23	600
T5A, T5B, T5C	1.34	600
T6A, T6B, T6C	1.34	0 (fan off)

* T1 = Flory 480 runs (control), T2–T6 = Flory 8770 runs.

Table 2. Details on the DPMS sampling missions at the 2 adjacent orchard plots located between the latitudes 36°29′58.2″ to 36°29′42.02″ North and the longitudes 119°23′8.45″ to 119°22′52.83″ West.

Location	Row(s)	Date	Start Time (PDT)	Stop Time (PDT)	Sampling Time (min)	Replicate Code
Plot a	13, 11, 12	24-Sep-18	11:42 AM, 02:05 PM, 02:10 PM	11:48 AM, 02:09 PM, 02:15 PM	4.2, 4.0 4.3	T2A
Plot a	4, 6, 5	24-Sep-18	03:27 PM, 03:32 PM, 03:40 PM	03:31 PM, 03:36 PM, 03:44 PM	4.0, 4.3, 4.0	T3A
Plot a	17, 19, 18	25-Sep-18	11:40 AM, 11:45 AM, 11:49 AM	11:43 AM, 11:48 AM, 11:53 AM	3.9, 4.0, 4.0	T4A
Plot a	20, 22, 21	25-Sep-18	01:23 PM, 01:30 PM, 01:43 PM	01:27 PM, 01:34 PM, 01:47 PM	4.2, 4.0, 4.1	T5A
Plot a	23, 25, 24	25-Sep-18	02:04 PM, 02:10 PM, 02:32 PM	02:08 PM, 02:14 PM, 02:36 PM	4.2, 4.0, 4.2	T6A
Plot a	26, 28, 27	25-Sep-18	3:12 PM, 3:19 PM, 3:21 PM	3:16 PM, 3:24 PM, 3:25 PM	4.2, 4.2, 4.1	T1A
Plot a	29, 31, 30	25-Sep-18	03:58 PM, 04:05 PM, 04:24 PM	04:02 PM, 04:09 PM, 04:28 PM	4.2, 4.0, 4.2	T2B
Plot a	32, 34, 33	26-Sep-18	8:45 AM, 8:50 AM, 9:01 AM	8:48 AM, 8:53 AM 9:04 AM	3.0, 2.9, 2.9	T3B
Plot a	35, 37, 36	26-Sep-18	09:48 AM, 9:56 AM, 10:02 AM	9:52 AM, 10:00 AM, 10:06 AM	4.1, 4.0, 4.2	T5B
Plot a	38, 40, 39	26-Sep-18	10:29 AM, 10:38 AM, 10:50 AM	10:33 AM, 10:42 AM, 10:54 AM	4.2, 4.2, 4.0	T1B
Plot a	41, 43, 42	26-Sep-18	11:14 AM, 11:19 AM, 11:24 AM	11:17 AM, 11:22 AM, 11:27 AM	3.0, 3.0, 2.9	T4B
Plot a	46, 45, 47	26-Sep-18	01:19 PM, 01:43 PM, 02:05 PM	01:23 PM, 01:47 PM, 02:09 PM	4.2, 4.2, 4.2	T6B
Plot a	50, 52, 51	26-Sep-18	03:03 PM, 03:09 PM, 03:28 PM	03:07 PM, 03:11 PM, 03:32 PM	4.1, 4.2, 4.2	T1C
Plot a	53, 55, 54	26-Sep-18	03:49 PM, 03:54 PM, 04:00 PM	03:52 PM, 03:57 PM, 04:03 PM	2.9, 3.0, 2.9	T3C

Table 2. *Cont.*

Location	Row(s)	Date	Start Time (PDT)	Stop Time (PDT)	Sampling Time (min)	Replicate Code
Plot a	56, 58	26-Sep-18	04:21 PM, 04:26 PM	04:24 PM, 04:29 PM	2.9, 3.0	T4C
Plot b	1, 3, 2	27-Sep-18	08:45 AM, 09:03 AM, 09:10 AM	08:49 AM, 09:07 AM, 09:14 AM	4.2, 4.1, 4.1	T2C
Plot b	4, 6, 5	27-Sep-18	09:24 AM, 09:30 AM, 09:35 AM	09:28 AM, 09:34 AM, 09:39 AM	4.1, 4.0, 4.1	T6C
Plot b	7, 9, 8	27-Sep-18	09:53 AM, 09:59 AM, 10:06 AM	09:57 AM, 10:03 AM, 10:10 AM	4.2, 4.1, 4.2	T5C
Plot b	10, 12, 11	27-Sep-18	10:43 AM, 10:53 AM, 11:07 AM	10:46 AM, 10:56 AM, 11:10 AM	2.9, 2.9, 2.9	T1E *
Plot b	13, 15, 14	27-Sep-18	11:23 AM, 11:33 AM, 11:45 AM	11:27 AM, 11:37 AM, 11:49 AM	4.2, 4.0, 4.2	T1D *

* Conventional harvest operation resumed to finish the nut-picking of all of Plot b. Harvesting of rows 10–15 was still recorded as additional control replicates.

2.3. Airborne Drone Particle Monitoring System

The airborne drone particle monitoring system (DPMS) was designed and developed for sampling solid particulates and partitioning them into the PM2.5, PM10, and TSP classifications. Each DPMS used a hexacopter rotary-wing UAV (DJI Matrice 600 Pro) with a maximum payload capacity of 6 kg, having a vertical hovering accuracy (P-GPS) of $\pm$0.5 m and a horizontal hovering accuracy of $\pm$1.5 m. The DPMS unit was powered via 22.8 V 5700 mAh lithium-polymer batteries (Figure 2a). A carbon fiber support airframe was fabricated to mount the PM sampler, with a 1/4″ diameter tube extending 5″ beyond the UAS propwash radius (Figure 2b). The fiber tube was used to position the sampling port outside of the propeller's downwash effect to minimize disturbance in the airflow intake. The sampler was internally powered using a lithium-ion rechargeable battery which, at full charge, was capable of 8 h of continuous operation. The drone is 6.25″ tall $\times$ 3.63″ wide $\times$ 2.0″ thick, with a gross weight of 1.75 lbs (0.79 kg), and can only be operated under ambient temperatures of 32 °F (0 °C) to 122 °F (50 °C). The calibrated airflow intake of the sampler was set to 0.10 ft^3/min or 2.84 l/min. The sensor used (AEROCET 831, MetOne, Grant Pass, OR, USA) counts and sizes ambient particles into different PM size ranges and converts the count data to mass measurements ($\mu g/m^3$) using an internally programmed proprietary algorithm (MetOne, Grant Pass, OR, USA). In effect, the sensor estimates a volume for each detected particle and assigns a standard density for mass conversion. A 40 mW 780 nm laser diode was the light source. The light-scattering principle for sensor operation is well discussed in this review article [16]. Since significant quantities of dust plumes are expected during harvest, the sampler was set to continuous mode under low sensitivity settings to avoid overloading the sensor. A Mobile Environmental Sensors and Subsystems, or MESS, Kit (Drone For Hire, Modesto, CA, USA) was used to provide geographic awareness data during each test. The higher altitude DPMS unit had a lightweight camera installed (Drone For Hire, Modesto, CA, USA) to record close-up dust plume footage. The total payload installed was below the safety limit, enabling the Matrice 600 Pro to have a reasonable average flight time of 25 min on a single battery charge. All flight missions were designed within that time window in order to accommodate times for takeoff, transit to and from the sampling location, and return to home for landing. A short inspection for each UAS was conducted every landing to ensure consistent functionality. Fully charged spare batteries were available at any time during the tests to minimize any sampling delays due to recharging.

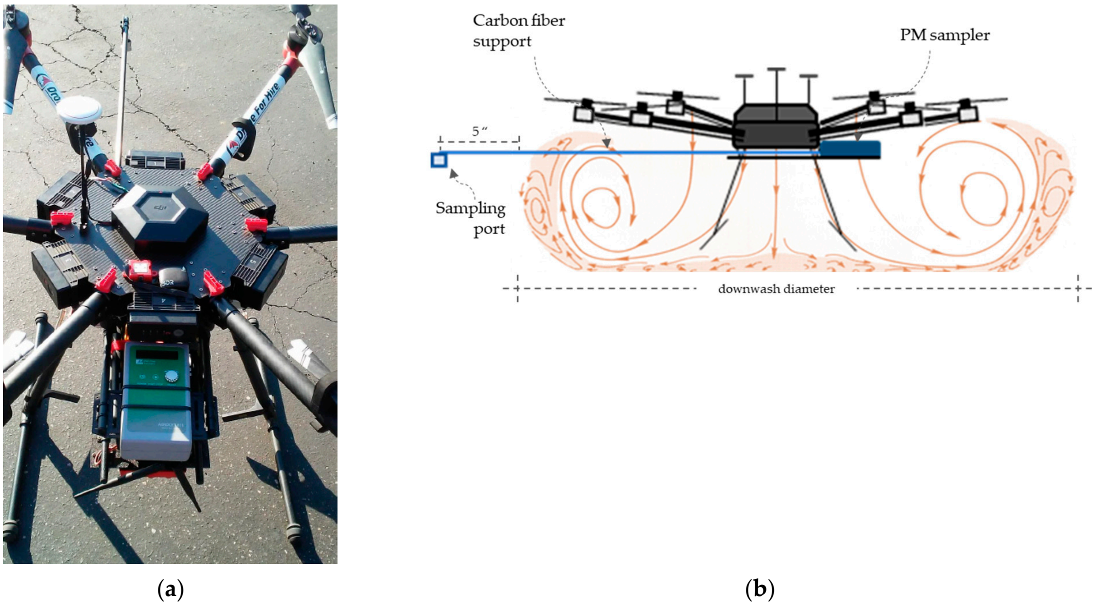


Figure 2. (**a**) PM sampler and MESS kit attached to the DJI Matrice Pro 600; (**b**) visual representation of the UAS propwash radius and position of the extended sampling port.

2.4. Flight Operations

In general, as the harvester starts to move forward along the row to pick up the windrow (nuts, soil, and other debris), simultaneous nut-picking and separation of dust happens. Continuous dust discharge creates a visible plume that trails the harvester (Figure 3a). The harvester continues to move forward and comes to a momentary stop once it reaches the end of the row. The dust plume settles after a few minutes, and the harvester moves to the next row to start the next run.

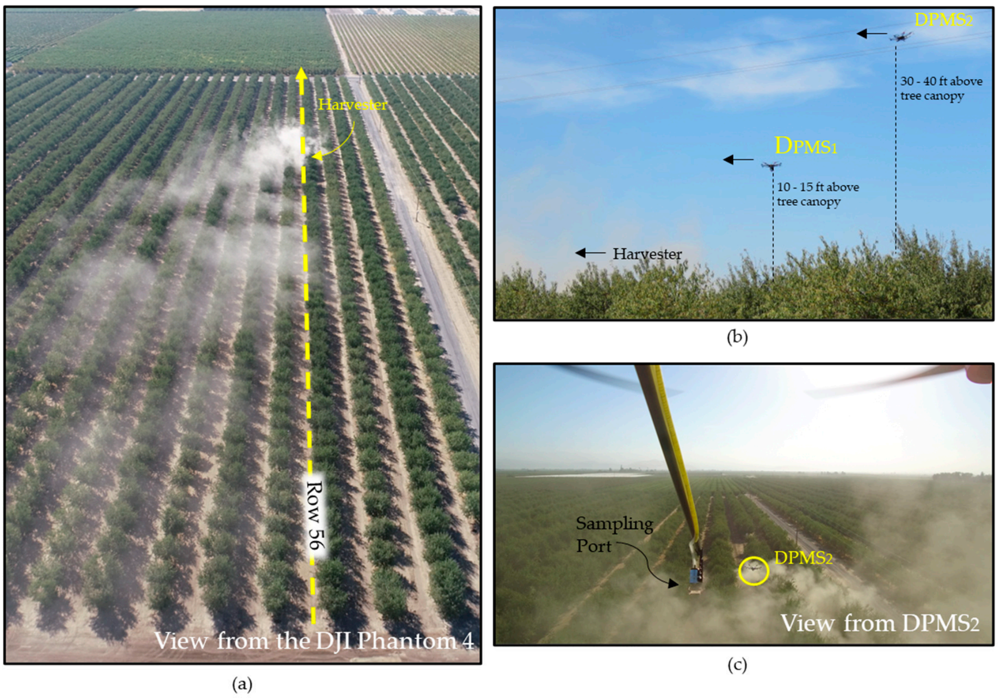


Figure 3. (**a**) Aerial view of the Row 56 being harvested, taken from a stationary Phantom 4 drone; (**b**) ground view of the nominal position of the two UAS (DPMS1 and DPMS 2) trailing the harvester; (**c**) mobile high-altitude view from DPMS2 of the DPMS1 during almond harvesting.

Two DPMS units were deployed at the same time to follow the harvester during each test (Figure 3b). The first UAS, DPMS1, maintained a position 10–15 ft (3.05–4.57 m) above the tree canopy while continuously adjusting its course depending on where the main plume was headed, based on prevailing wind direction. The second UAS, DPMS2, maintained a position 30–40 ft (9.14–12.19 m) above the tree canopies. Its main purpose was to capture high-altitude dust dispersion downwind of the harvester (Figure 3c). Two other DPMS units were on standby. Two Phantom 4 drones (DJI, Shenzhen, China) were alternately used to capture high-definition (HD) aerial video footage of the entire row being harvested as shown in Figure 3a.

Particulate sampling using the DPMS was conducted simultaneously with the harvesting based on the approved operational settings shown in Table 1. The DPMS units performed mobile aerial sampling missions based on the schedule logs shown in Table 2. During each replication, three rows were harvested with enough pauses in between row runs to allow for dust settling, machinery check-up, and drone inspection. For each sampling mission (1 row per mission), the DPMS was flown into position and held in "positioning mode" at the altitudes denoted in Figure 3b while waiting for the harvester to be in position at the start of the harvest row. The DPMS pilots were instructed to follow the dust plume at each specified altitude. Each sampling mission was terminated once the harvester reached the end of the harvest row. The entirety of Plot a was harvested for 3 days, while a portion of Plot b was harvested on the 4th day to complete all replicate runs. Each harvest row was about 0.24 miles in length, while some of Plot a's harvest row was about 0.21 miles in length (Figure 1). The sampling time recorded during all the sampling missions was found to be consistent for all replicate runs at both 3 mph (1.34 m/s) and 5 mph (2.23 m/s) (Table 2).

2.5. Data Analyses

After all replicate runs were completed for each day, all stored PM data were downloaded in CSV files and opened in Microsoft Excel for trimming and alignment. The JMP® Pro 16 (SAS Institute Inc., Cary, NC, USA) was used to perform all data handling and statistical analyses. The data were analyzed for extremeness (outliers) by summarizing all sampling points for each replicate into a standard outlier box plot following the 1.5 x Inter-Quartile Rule [17]. The final PM levels for each treatment were reported as means and standard errors. Analysis of variance (ANOVA) tests were conducted to determine whether differences existed in the means of PM levels generated by the harvester at varying fan speeds and forward ground speeds. The null hypothesis tested was that the mean PM levels from each treatment were equal. A p-value < 0.05 was considered statistically significant. In the case of data sets that deviated to some degree from the normality assumption, an analogous nonparametric test (Kruskal–Wallis one-way ANOVA) was run to confirm results when appropriate. Furthermore, a full-factorial multiple regression model using standard least squares was used to investigate the main effects and interactions of local meteorological factors and operational changes to the measured PM levels.

The means of the main plume PM data were used to estimate potential PM reductions by % that can be achieved by using a low-dust harvester in comparison to a conventional harvester (control). The resulting reduction estimates were then compared to previous findings using other PM dust measurement systems. The PM reductions were estimated based on Equation (1),

$$\%\text{ PM Reduction}_{i,j} = (\text{PM}_j \text{ old harvester} - \text{PM}_{ij} \text{ low-dust harvester})/\text{PM}_j \text{ old harvester} \times 100 \quad (1)$$

where:

i represents the treatment (T2–T6)
j represents the specific PM cut (PM2.5, PM10, TSP)

3. Results and Discussion

3.1. Daily Meteorological Variations

Orchard field temperatures in September can reach highs of 98 °F (36.67 °C), which were observed during the study period. Average daytime temperatures ranging between 84.38 and 88.87 °F (29.1–31.59 °C), mean low humidity from 25 to 32%, moderate mean wind speeds of 3–4 m/s, and equal portions of clear skies in the morning and hazy conditions in the afternoon were observed from meteorological data (Figure 4). Resultant winds primarily blew from the southwest for the entire testing period. For this study, Days 2 and 3 only experienced higher wind speeds of 4.5–6.5 m/s about 25% of the time, while Day 3 (afternoon not included) saw them about 50% of the time. The light to moderate wind speeds resulted in slow dispersion of dust, which provided enough time for the DPMS units to adjust its course and accurately follow the dust plume. These local weather data collected at a height of 23 ft (7 m) were considered representative of the atmospheric layer conditions near the canopy of the almond trees (average height of 20 ft, or 6.1 m).

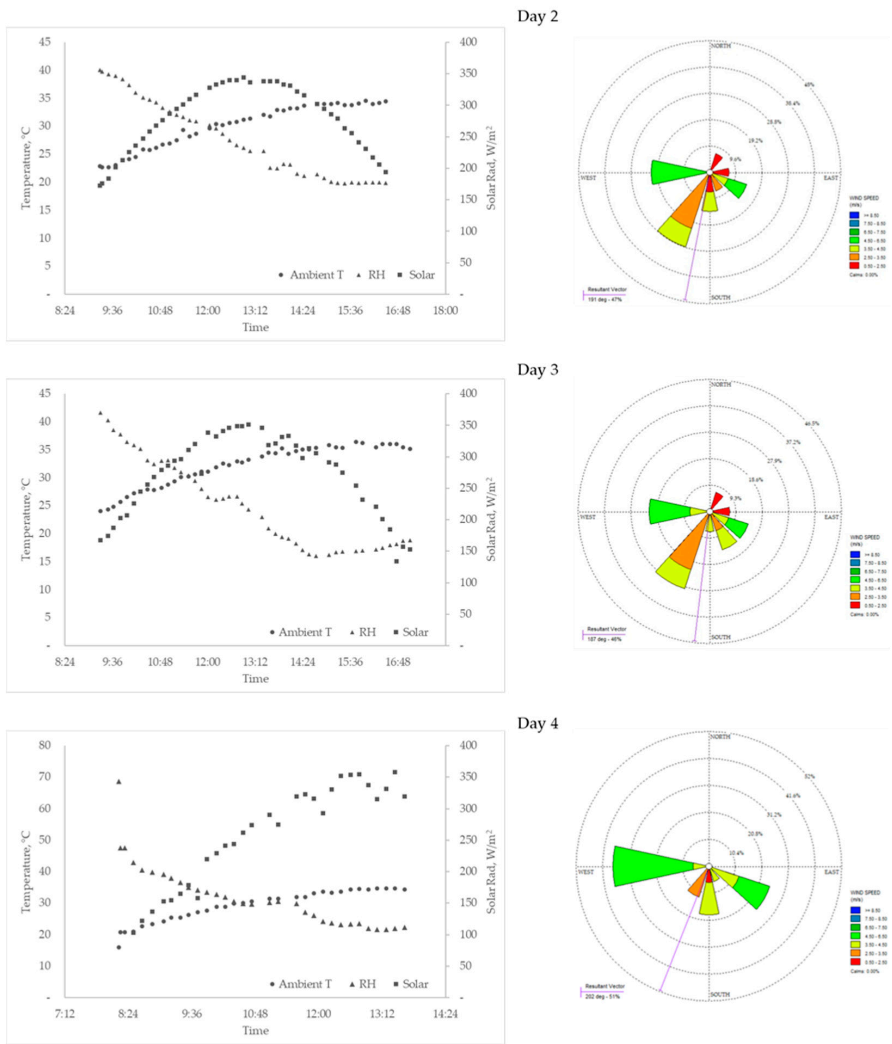


Figure 4. Local ambient meteorological data from an on-site, 7-m weather station. Day 1 data were not available due to a logger communication error.

3.2. PM Levels at Various Harvester Operational Settings

A total of 60 flights were conducted to cover both Plots a and b as shown earlier in Table 2. The spatial distribution of PM sampling points across the entire study area is shown in Figure 5, with the exception of Day 1 (Rows 1–15), when flight coordinates were not available due to issues with the telemetry set-up. The attributes of the points shown are measured PM concentrations corresponding to their relative sampling position. Most of the rows harvested by the earlier/conventional harvester generated dust plumes which consistently contained high levels of TSPs, PM10s, and PM2.5s compared to the newer/low-dust harvester operated at various settings (T2–T6). The variations in PM levels across treatments were apparent, but on average, the lowest PM levels were obtained when the harvester was operated at low speed and no fan settings. A still-closer look at Figure 5 reveals that the highest PM levels measured (red dots) were observed during the majority of the control runs, while the PM levels of other treatment runs generally trended lower. The TSP and PM10 raw concentrations measured ranged from about 120 μg/m^3 to high concentrations of 9000–10,000 μg/m^3. For PM2.5s, the range of measured concentrations was between 1 and 1965 μg/m^3.

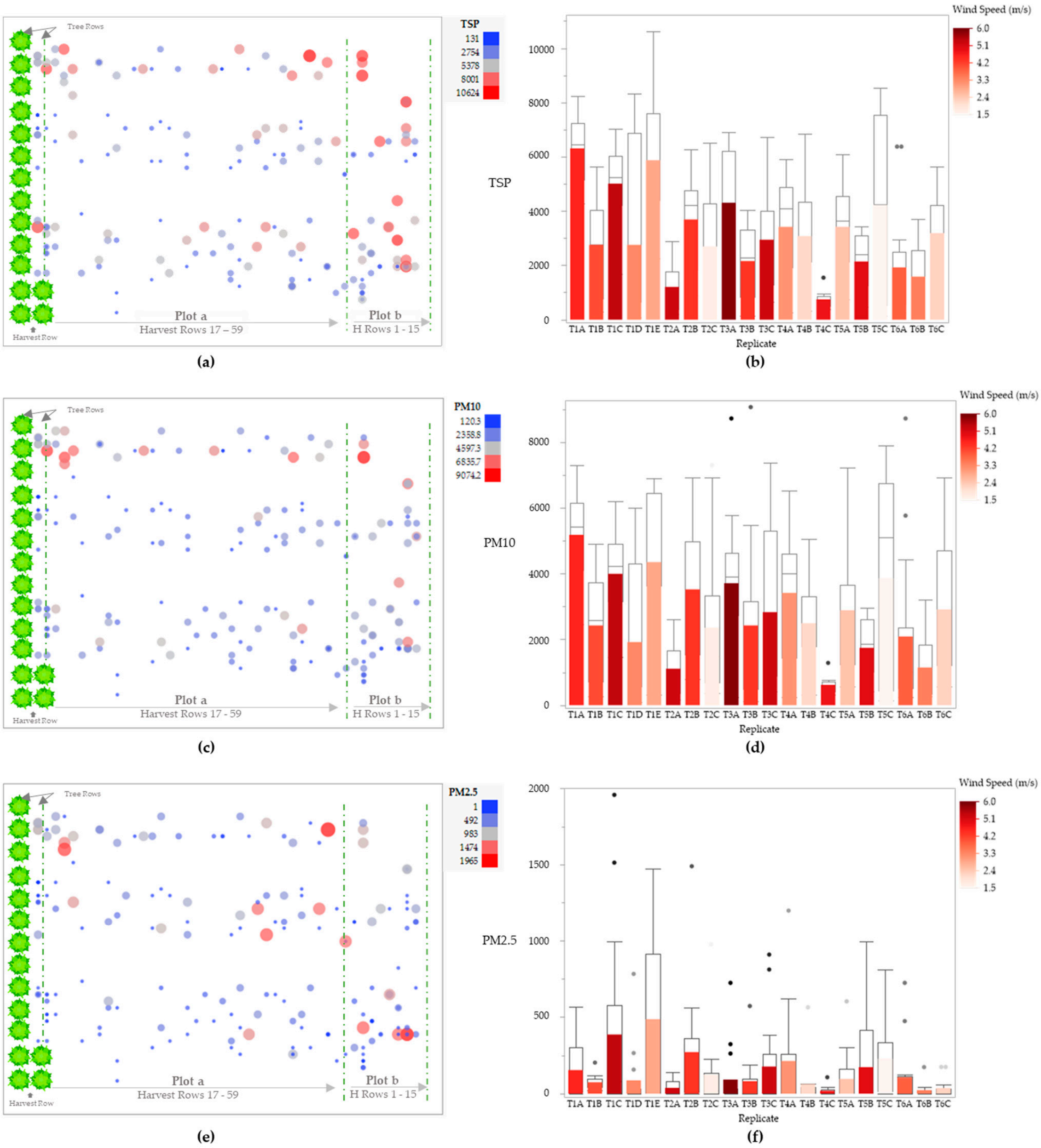


Figure 5. Raw PM data distribution from the study orchard illustrating the type of PM, magnitudes, and sampling positions (**a**,**c**,**e**) and outlier standard box plots for each replicate at different wind speed regimes (**b**,**d**,**f**). Day 1 meteorological data were obtained from Visalia Municipal Airport (VIS), 36.19N, 119.24W, 292 ft (89 m) elevation.

The high PM levels reported in this study were measured directly 10–15 ft above the tree canopy, within the orchard boundaries. In general, the US Occupational Safety and Health Administration (OSHA) has the legal authority to regulate worker safety and health within the work area. OSHA's Permissible Exposure Limit (PEL) of airborne concentrations of PM10s (respirable fraction) is 5 mg/m^3 or 5000 $\mu g/m^3$, 8-hr total weighted average (TWA) and of TSPs is 15 mg/m^3 or 15,000 $\mu g/m^3$ 8-hr TWA, for total dust [18]. The average PM10 concentrations for all sampling missions trended lower than the PM10 PEL, except for one control run (T1A), as presented in Figure 5. The average of all TSPs measured generated by the new harvester trended lower than those of all control runs and was observed to be lower than the TSP PEL. In some cases, it is recommended that PM10 airborne concentrations be kept under 3 mg/m^3. Operating at lower fan speed (T4) and low speed, no fan settings (T6) were able to achieve PM10 levels below the threshold limit value (TLV) [18]. Based on these results, the use of an older harvester generates airborne dust that will likely exceed the conservative PM10 TLV. Orchard owners are required to initiate dust mitigation options, including the use of personal protective equipment to protect harvest operators and workers. Using a low-dust harvester, particularly at low fan speeds, is one way to reduce PM emissions down to a level below the PEL, thereby reducing any significant risk to the health of the workers during harvesting. For allowable limits of dust concentration outside the property line of the harvested orchard, the US EPA's PM NAAQS are often adopted as the regulatory standard. The PM NAAQS are known to be more stringent and is used to monitor the PM effects on the public health and welfare, downwind of an emission source [19]. This would require fence line monitoring of PM concentrations which is beyond the scope of this study.

Before statistical analysis, data were analyzed for outliers and to ensure that the conditions required for a standard ANOVA were satisfied. Figure 5 shows the average PM concentrations for each replicate with specific box plots to illustrate the spread of data and to visually check for normality and identify potential outliers (represented by dots). After extremely high values were omitted, which can primarily be attributed to momentary sensor noise, a log transformation was applied to the TSP and PM concentrations, while a power transformation ($\lambda = -0.091$) using the JMP's box–cox plot was applied to the PM2.5 concentrations to produce normally distributed transformed data following a similar approach to previous FRM emissions data handling [4]. The transformed data were able to approximate constant variance between treatments (TSP-Levene's p-value = 0.7569; PM10- Levene's p-value = 0.8842, PM2.5-Levene's p-value = 0.0423). Parametric tests such as the standard ANOVA are generally quite robust, which means they can perform reasonably well even if the data deviate to some extent from the assumptions. Since PM2.5 measurements did not strictly adhere to the normality assumption, an analogous non-parametric test using the Kruskall–Wallis test [20] was conducted to confirm the results.

In terms of TSP emissions, one-way ANOVA results showed a statistically significant difference in the mean TSP levels between at least two treatments ($F = 4.65$, $p = 0.0004$). Student's t-test for pairwise comparison between treatments indicates that the mean TSP levels of harvest dust generated from the control harvester were significantly higher compared to those of the low-dust harvester operating at the following settings: low speed, no fan (T6) at $p = 0.0001$, standard (T2) at $p = 0.0019$, high speed, and low fan (T4) at $p = 0.0035$. On the other hand, the difference between the means of the control to the high speed, standard fan (T3) at $p = 0.0557$ and low speed, low flow (T5) at $p = 0.0575$ were not significant. The mean ordered differences within T2–T6 were all found to be not significant.

In terms of PM10 emissions, one-way ANOVA results showed a statistically significant difference in the mean PM levels between at least two treatments ($F = 3.41$, $p = 0.0053$). Student's t-test for pairwise comparison between treatments indicates that the mean PM10 levels of harvest dust generated from the control harvester were significantly higher compared to those of the low-dust harvester operating at the following settings: low speed, no fan (T6) at $p = 0.0001$, standard (T2) at $p = 0.0117$, high speed, and low fan (T4) at $p = 0.0242$. On the other hand, the difference between the means of the control and the high-speed, standard fan (T3) at $p = 0.0779$ and low-speed, low-flow fan (T5) at $p = 0.0947$ were not significant. The mean ordered differences within T2–T6 were all found to be not significant.

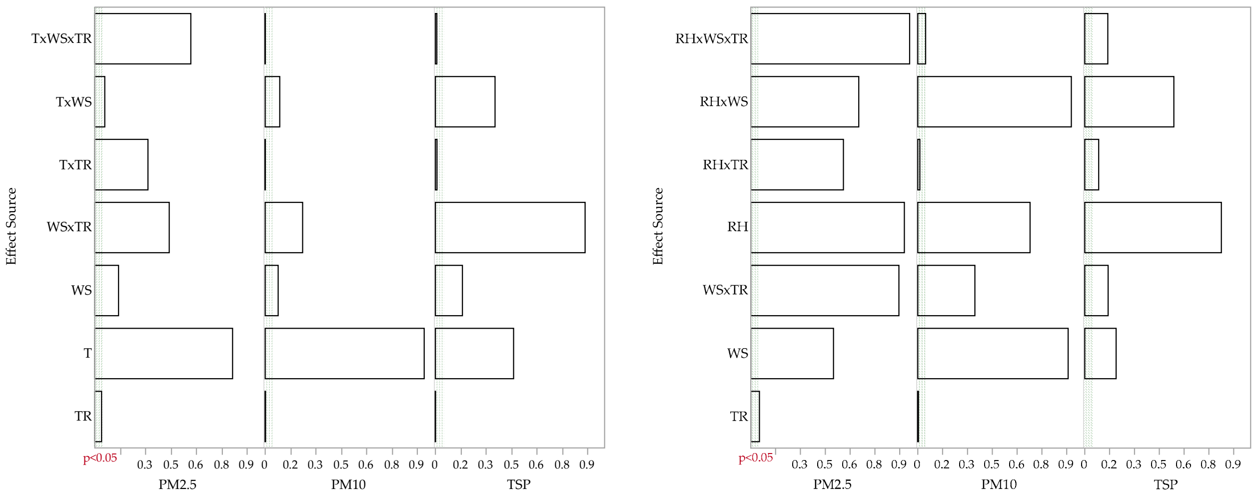
In terms of PM2.5 emissions, the results of the one-way ANOVA revealed there was a statistically significant difference in the mean PM2.5 levels between at least two treatments ($F = 6.04$, $p = 0.0001$). Student's t-test for pairwise comparison between treatments indicated a different trend than that of the TSP and PM10 concentrations. The mean 2.5 levels of dust plume coming from the control harvester were significantly different from T3 ($p = 0.0001$) and T6 ($p = 0.0001$) only. Meanwhile, within comparisons of mean PM2.5 emissions of the low-dust harvester running at various operational settings (T2–T6) revealed that T2, T5, and T4 settings produced dust plumes having different PM2.5 levels. The Kruskal–Wallis test also revealed that there was a significant difference between the treatment levels with respect to the PM2.5 measurements ($p = 0.0001$) and agrees with each pair mean comparison results, further validating the ANOVA robustness.

3.3. Effects Analysis of Meteorological Factors and Operational Changes to the DPMS Data

Wind speed (WS), temperature (T), and relative humidity (RH) were investigated for their effects on the DPMS data. A full-factorial multiple regression model test was conducted using JMP software for the purpose of identifying important variable effects and understanding (rather than predicting) their influence on the PM measurements [21,22].

The effects of meteorological factors and atmospheric chemical process (e.g., deposition and transformations) on airborne particle distribution are known to be mutual and coupled [23]. For this study, these chemical processes were not investigated and, within the study's limited spatiotemporal boundary, were assumed to have negligible effects given the physical nature of the dust generation process, no precipitation and relatively low humidity conditions, and absence of any significant source of precursors for secondary formations. The mutual relationship between explanatory factors is termed multicollinearity. The presence of collinearity leads to inflated standard errors and false non-significant *p*-values in identifying important variables. The variance inflation factor (VIF) is a measure of variance of regression coefficients and describes the strength of the correlation between independent variables. A VIF of greater than 5 to 10 usually indicates that multicollinearity might be an issue [24]. The T and RH had a high VIF with a range of 66 to 77, while the rest of the variables were well below the threshold. The multivariate correlation coefficients of T and RH were -0.96, indicating a very strong negative correlation and validating the high VIF score.

Two sets of explanatory models were tested to decouple the effects of T and RH. Preliminary residual analyses verified that the conditions of drawing inferences from the model effects have been met. The effects analysis for the study variables are shown in Figure 6, where *p*-values are compared based on the null hypothesis that a particular variable or its interactions has no effect on the measured PM data. A $p\text{-value} < 0.05$ indicates enough statistical evidence to reject that null hypothesis. For both models, the operational settings (TR) were found to be the most important variable in explaining the response (PM measurements) with highly significant *p*-values for all PM levels. The main effects of all other variables were not significant. However, the interaction effects of T and RH to TR were found to be slightly significant, particularly for PM10 data outcomes. Harvests conducted at high RH/low T will likely result in fewer collected PM10s as increased RH generally encourages dry deposition, reducing PM10 concentrations in the atmosphere [23]. The interaction effects of T and WS with operational settings should be considered in explaining PM10 and TSP levels. Low WS and high T have slight positive correlations with both PM measurements, which trended similarly with some of the most recent air quality monitoring studies [15,25,26]. Results further imply that a slow dispersion of the dust plume due to WS-T effects provides the DPMS units ample time to sample PM but with a chance of TSP over-sensing, as TSPs can easily accumulate and overload the sensor at very low WS conditions [27]. When this happens, it is recommended that the operators regularly clean/replace the sampling tube after a series of low-WS flight missions.



(**a**) (**b**)

Figure 6. Effects summary of different explanatory variables (in terms of *p*-values) for measured PMs generated from multiple regression models using standard least squares. All *p*-values below the shaded region ($p < 0.05$) indicate important effects. Two models were constructed to decouple the effects of (**a**) temperature and (**b**) relative humidity.

For PM2.5 measurements, the WS-T effects were also found to be significant. In general, large variability in the PM2.5 data (as previously illustrated in Figure 5f) was observed for measurements taken at wind speeds ≥4 m/s. Despite the careful maneuvering of the DPMS units to maintain proximity to the main plume, wind speeds ≥4 m/s produced several PM2.5 outlier points (20.25%). It was possible that with the current sampler head orientation, the intake flowrate towards the sensor is significantly lower than the speed of particles at high wind speeds, thereby reducing the effectiveness of the DPMS in properly capturing PM2.5s from the dust plume. In most high-PM scenarios, the recommended sensor setting was at low sensitivity, resulting in the DPMS's low precision performance in detecting particles in the ≤2.5 µm size range.

3.4. Vertical PM Concentration at Various Operational Settings

Average PM concentrations (with standard errors) obtained via the DPMS2 generally trended lower compared to those obtained via DPMS1 across all treatment levels (Figure 7). The generalized vertical PM profile indicates concentrations near the plume (10–15 ft or 3.05–4.57 m above the tree canopy) that were higher by 1.1 to 2.3 orders of magnitude than the concentrations recorded at 30–40 ft above the tree canopy. For both altitudes, operation at low speed and no fan setting resulted in the lowest measured concentrations across all PM cuts. However, for high-intensity dust plumes, the measured PM concentrations at higher elevations were not intuitive of the operational settings, i.e., control runs (T1) had lower average PM levels than the other dust mitigation settings. As presented earlier, there was enough statistical evidence to show that interaction effects of WS, particularly at ≥4 m/s, affect sensor performance. At 30–40 ft (9.14–12.19 m) above the canopy, the magnitude of wind speeds was assumed to be higher due to lower gravitational and canopy friction effects. A decrease in PM levels can be observed with increased wind speeds [13,15]; however, this could also be a factor that might lead to inconsistencies in PM readings as observed from the DPMS measurements. As it stands, the DPMS measurements at 10–15 ft (3.05–4.57 m) above the tree canopy were found to better represent the changes in the dust plume intensities as a function of harvester's operational settings.

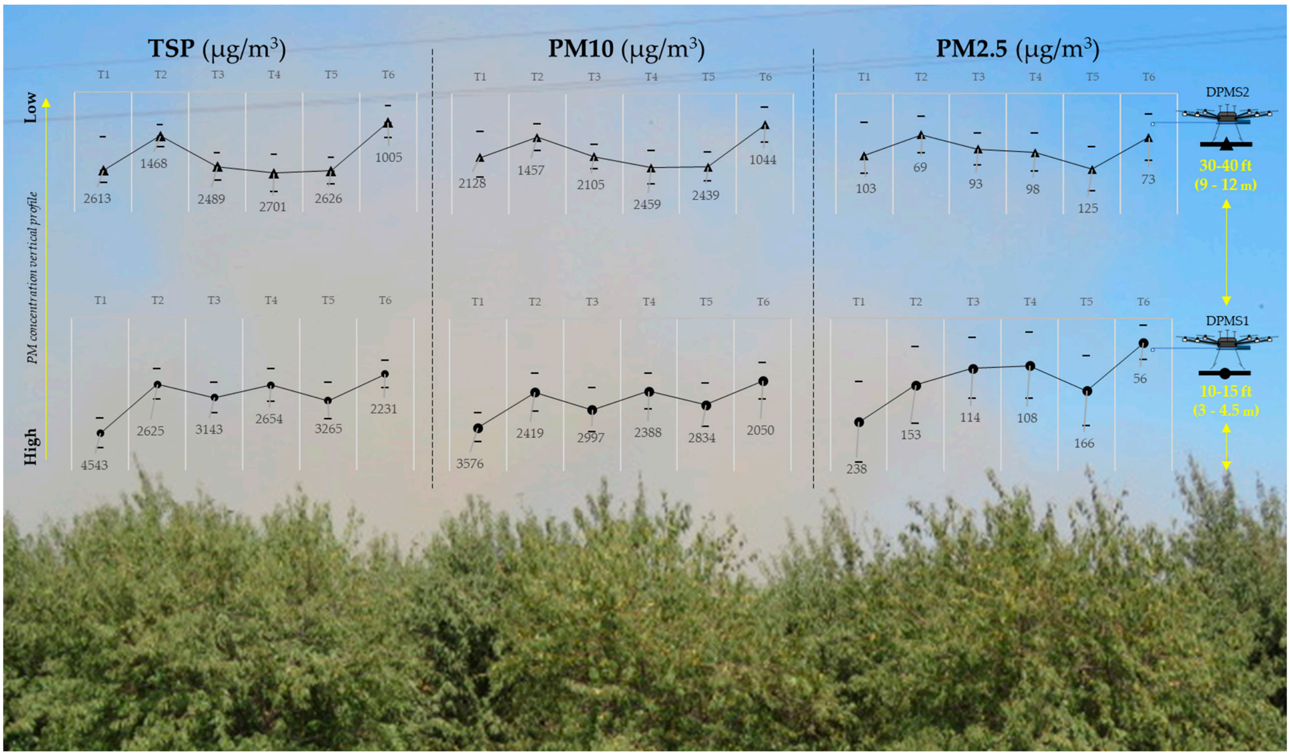


Figure 7. Average PM concentrations as a function of operational settings (T1–T6) at two different sampling altitudes.

3.5. PM Reduction Estimate

Using the average PM measurements at near above canopy (DPMS1), the PM reductions were estimated using the control PM levels as the baseline (Table 3). For example, the degree of TSP reduction associated with operating at low speed and the no-fan setting can be estimated using Equation (1) as shown below,

$$\%\ \text{TSP Reduction}_{T6} = (4543\ \mu\text{g/m}^3 - 2231\ \mu\text{g/m}^3)/4543\ \mu\text{g/m}^3 \times 100 = 50.90\%$$

Table 3. PM reduction estimates (%) from using a low-dust almond harvester based on three different dust measurement systems at two different periods (2017 and 2018).

TR Code	Operational Setting (Ground Speed, Fan Speed)	Aerial-Based, Mobile, Non-FRM			Method 9, Visual Opacity, Non-FRM [c]	Ground-Based, Stationary, FRM [d]		
		PM2.5	PM10	TSP	TSP	PM2.5	PM10	TSP
T1 [a]	1.34 m/s, 900 rpm [b]	—	—	—	-	-	-	-
T2	1.34 m/s, 900 rpm	35.67	32.35	42.23	40.12%	44%	56%	51%
T3	2.23 m/s, 900 rpm	51.97	16.20	30.82	16.41%	n/a [e]	n/a	n/a
T4	2.23 m/s, 600 rpm	54.45	33.22	41.59	57.86%	n/a	n/a	n/a
T5	1.34 m/s, 600 rpm	30.16	20.75	28.15	14.99%	n/a	n/a	n/a
T6	1.34 m/s, fan off	76.51	42.68	50.90	66.37%	n/a	n/a	n/a

[a] T1 = control, baseline PM level; [b] 3 mph, 900 rpm is the conventional/standard harvester setting; [c] Method 9 visible harvest dust (TSP) visual opacity results [9] concurrently performed with this study; [d] FRM PM reduction based on emission factor comparison. Flory low-dust harvester was only tested at conventional setting [2]; [e] n/a = not available.

The final average PM levels measured from the dust emissions of the new harvester have shown positive reductions compared to those of an old harvester. The dust reduction estimates of using a new harvester at various operational settings produced closely similar trends, particularly for PM10 and TSP emissions. When compared to the older harvester, a newer harvester operated at standard settings (T2) produced 35% fewer PM2.5s, 32% fewer PM10s, and 42% fewer TSPs. For this study, the new harvester (Flory 8770) is designed with industry leading cleaning chains resulting to lower PM emissions despite running at similar standard settings to that of the control. Increasing the ground speed had an adverse effect on dust mitigation. The new harvester at faster ground speed was only able to reduce PM10 by 16% and TSP by 31%. On the other hand, reducing the new harvester's fan speed offered only a slight advantage in dust reduction compared to operating at standard setting. Both of these operational changes showed large reduction estimates in PM2.5 within the range of 50–70%. The highest PM reductions were achieved when the harvester was running at reduced speeds and when separation fan was turned off, producing 43% fewer PM10 and 51% fewer TSP. In practice, operators will not simply turn off the blower fan since this will encourage accumulation of dust towards the harvester. Meanwhile, the low ground speed coupled with low fan speed showed inferior dust reduction estimates which was not very intuitive. It was observed that majority of the T5 runs were randomly assigned at hours with low wind speed conditions (1.7–2.1 m/s) which likely resulted to a positive bias, thereby registering higher measured PM readings. An incorrect operator adjustment and/or execution to the harvester settings could also be possible. Caution should be used in drawing conclusion regarding both the T5 setting and the PM2.5 reduction estimates given the large variability in the PM2.5 data set. Hence, both results need to be further evaluated with improved data resolution.

The newer harvester tested in this study was able to demonstrate that moderate adjustments in the operational settings is a practical option for orchard owners to reduce harvest dust. The TSP reduction estimates based on aerial PM emissions was able to show a similar trend, with a nominal difference of 10–15% points in the visible dust (TSP) reductions estimated from a concurrent study using visual emission evaluation techniques [9]. Meanwhile, a 2017 FRM-based field study using a Flory low-dust harvester operated at standard settings was able to demonstrate PM reduction estimates which were slightly higher yet trended similarly with the results of the current non-FRM aerial-based study. These slight differences might be attributed to the difference in the dust measurement methods, meteorological conditions, and confounding variables such as orchard soil structure and management practices. More importantly, these results indicate that the DPMS protocol tested in this study was able to provide substantial data for detecting changes in PM levels and rapid assessment of dust mitigation measures on-site.

4. Conclusions

In this study, the DPMS protocol demonstrates the feasibility of aerial dust measurements during almond harvesting. The possible effects of wind direction were assumed to be negligible by careful DPMS unit maneuvering to follow the harvest dust plume. The mutual effects of other meteorological factors (T, WS, and RH) were found to be slightly correlated with the PM10 and TSP readings; however, the aerial DPMS was able to perform well within acceptable statistical levels of confidence. The significant correlation of WS and T with PM2.5 measurements resulted in large data variability, which could be attributed to the sensor's low sensitivity at high dust plume intensities and possible unstable airflow intake in the sampler during high wind speed conditions. A sensor that can produce a better data resolution could be used to increase statistical power and to validate the influence of outliers on the overall airborne particle distribution obtained from the DPMS. Aerial particle monitoring and sampling should be conducted at elevations close to the tree canopy to reduce the data variability due to WS coupled effects.

The DPMS units were able to detect changes in dust concentrations by implementing moderate modifications to harvester settings. The newer harvester was able to produce significantly fewer PM emissions than an older harvester operating at similar standard settings. Reducing ground speed by half resulted in a slightly more favorable margin. Reducing both the ground speed and fan flow should intuitively result to further dust reduction; however, the findings imply otherwise, which warrants further investigation. As it stands, the dust reduction estimates of the present aerial-based PM study were able to show agreement with the results of other dust measurement systems (e.g., visual evaluation and FRM), with some discrepancies which can likely be attributed to the difference in the methods, meteorological context, and confounding effects of orchard soil structure and management practices.

Immediate on-site assessment of dust reduction options is a clear advantage of the DPMS, with minimal disruption to existing orchard practices. Ground-based samplers are dependent on wind speed and direction in order to capture downwind PM concentrations that represent the source emissions. In most cases, the positioning of FRM samplers is critical to accurately estimating PM emission factors which are the basis for dust reduction assessment. By directly measuring aerial PM concentrations at the source, the proposed use of DPMS reduces logistical needs, complexity issues, and feedback times compared to the FRM protocol. However, the DPMS data are still unlikely to replace the accuracy and precision of mass-based FRM data, and their robustness should be investigated at different orchard locations. Additional work is needed to elucidate potential correlation of DPMS data to ground-based FRM data by testing both protocols side-by-side. At this stage, this aerial DPMS protocol is considered non-FRM and should only be used as a rapid screening tool to complement the existing FRM for evaluating dust abatement strategies and not for regulatory purposes.

Author Contributions: Conceptualization, S.C.C.; Methodology, S.C.C.; Formal analysis, E.J.N.B.; Investigation, E.J.N.B. and S.C.C.; Writing—original draft, E.J.N.B.; Writing—review & editing, E.J.N.B. and S.C.C.; Visualization, E.J.N.B.; Supervision, S.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was mainly funded by Almond Board of California with partial funding from San Joaquin Valley Air Pollution Control District, Project No.17.AIRS3.ESJVAD/Capareda.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, [E.J.N.B.], upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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