Dynamic evaporation of droplet with adjuvants under different environment conditions

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Abstract: Pesticide droplet is evaporating during the falling from the nozzle to the target. This dynamic evaporation is influenced by ambient temperature, relative humidity (RH), adjuvant type and concentration. In the evaporation process, the droplet size at different height is affected by the droplet evaporation. Based on this, this study determined the droplet dynamic evaporation by collecting the droplets from different height via silicone oil method with a certain temperature and RH. Eight adjuvants were chosen, including three organo-silicon, three vegetable oil and two non-ionic, with five concentrations. All droplets were generated by a droplet generator. The results showed that the type of adjuvant, ambient temperature and RH had no significant influence on droplet size generated by droplet generator. All the adjuvants in this experiment cannot reduce dynamic evaporation; Concentration of adjuvant made a difference in dynamic evaporation. This could be because of the property of adjuvant. Organo-silicon adjuvants have a negative correlation with water vapor pressure, it showed less dynamic evaporation at high temperature and RH. Vegetable oil and non-ionic adjuvant, they are the same as the controlled blank that the dynamic evaporation reduces with decreasing temperature and increasing RH.
Keywords: pesticide droplet, dynamic evaporation, adjuvant, temperature, relative humidity
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1 Introduction

Plant protection product (PPP) is known as the main method in plant protection, which is faster and more efficient than physical and biological methods at present. It makes PPP plays a very important role in agricultural production[1]. However, there is always pesticide drift produced during the pesticide application process, which may cause many problems such as contamination of the environment, pesticide residues and phytotoxicity[2]. Vapor drift, one type of drift, is the active ingredient of pesticides evaporated into the air during or after the application.

There are two types of pesticide droplet evaporation: static evaporation and dynamic evaporation. Static evaporation is that liquid evaporates under stationary condition, such as the droplets evaporate on the leaf. The evaporation is evaluated by commonly measuring the decreased weight of droplet on the target at a certain time[3,4]. Dynamic evaporation is that liquid evaporates in dynamic conditions, such as evaporation in the flying process. Evaporation speed of the pesticide droplet has a significant effect on the efficiency of pesticide: if the droplets evaporated too fast, a large quantity of solutions would evaporate during the flying process which would cause pesticide loss. Besides, high evaporation speed might cause the active ingredient of pesticide to crystallize after the droplets reached to the target[3,5], which could reduce the pesticide efficiency because the absorption of the pesticide would be almost stopped after droplet completely evaporated[6].

There is no obvious relationship between active ingredient pesticide and droplet evaporation[7]. Factors of affected on droplet evaporation consist of ambient temperature, relative humidity, airflow velocity, droplet temperature[8-10], as well as the micro-structure of the target surface, droplet size, adjuvant and concentration[11-13]. The droplet size is the primary factor affected evaporation and drift. The drift of small droplets with a lower falling velocity is higher than that of bigger droplets and higher temperatures also could increase the evaporation[14]. Droplet size could be adjusted by the different types of nozzle and spraying pressure[15], which also could be adjusted by adding adjuvants to change the surface tension of liquid[16,17], this also could improve the efficiency of pesticide[18]. Different types and concentrations of adjuvants may cause distinct effects on droplet evaporation, surfactant[19-21].

As for simulation calculation of droplet evaporation, Goering did simulation calculation of droplets which diameter is 0.3 mm to 2 mm[22]; Marchant found a 3D equation for calculating droplet moving velocity in 1977[23], which was improved by Cox SJ in 2000[24]. Based on Goering's research, Liu combined the droplet evaporation model with a droplet motion model and analyzed the VMD of the droplet from the 4.8 mm sprinkler spray nozzle and predicted droplet evaporation[9]. Though there has been a simulation for calculating droplet evaporation, the reliability of this simulation is still unknown. It needs more measurements to determine the accuracy of the simulation calculation.

Nowadays, the unmanned aerial vehicle (UAV) is being developed rapidly, especially in China. Droplets of UAV spray

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has long movement distance (1.5-4.0 m) to target, which causes great evaporation during the droplet moving process. Therefore, the evaporation of droplets is unignored in the application process, especially with long movement distance such as UAV spraying. Many kinds of research have studied droplets drift and deposition distribution of UAV[25-27], while few are related to dynamic evaporation. The main goal of this research is to investigate the effects of ambient temperature, relative humidity, adjuvants types and concentrations on droplets dynamic evaporation through experiments, find out the appropriate environment condition for adjuvant application and provide a reference for PPP, particularly in UAV spraying.

2 Materials and methods

This research is about the dynamic evaporation of droplets, and the experiment was conducted in the wind tunnel in the Institute for Application Techniques in Plant Protection of Julius-Kühn-Institut (JKI, Federal Research Center for Cultivated Plants, Germany). The dynamic evaporation process is defined as evaporation in the process of droplet movement and was determined by measuring the droplet size through droplets fall from the droplet generator's needle.

Eight adjuvants were selected and five concentrations of each adjuvant were set in this research (Table 1) mixed with 0.25 g/L Fluorescein sodium solution (in deionized water). The five concentrations were based on the recommended concentration (RC) provided by the manufacturers, which are shown in Table 1, where the third concentration of each adjuvant is the RC. The controlled blank (CK) was set as a non-adjuvant (0.25 g/L fluorescein sodium solution) to reduce the effect of tracer The temperature of all the liquids before spraying was 20 ℃ to avoid the effect of different environment temperature in this study.

Table 1 Adjuvants at various concentrations

Adjuvants	Type	Manufacturer	Concentrations/% v/v				
			1	2	3 (RC)	4	5
S903	Organo-silicon	Grand Agro Chem Co., Ltd (Beijing, China)	0.01	0.02	0.05	0.10	0.20
Silwet-408	Organo-silicon	Momentive Performance Materials Inc (New York city, USA)	0.01	0.02	0.03	0.05	0.10
Greenwet3710	Organo-silicon	Green-Times Technology Co., Ltd (Beijing, China)	0.01	0.02	0.03	0.05	0.10
Greenwet3718	Vegetable oil	Green-Times Technology Co., Ltd (Beijing, China)	0.10	0.20	0.30	0.50	1.00
Tmax	Vegetable oil	Grand Agro Chem Co., Ltd (Beijing, China)	0.10	0.20	0.30	0.50	1.00
Hasten	Vegetable oil	Victorian Chemical Company Pty Ltd (Melbourne, Australia)	0.10	0.20	0.30	0.50	1.00
Greenwet360	Non-ionic	Green-Times Technology Co., Ltd (Beijing, China)	0.10	0.20	0.30	0.50	1.00
NDR-11	Non-ionic	Numen(Beijing) international biotech co., Ltd (Beijing, China)	0.03125	0.0625	0.125	0.25	0.50
CK (no adjuvant)	/	/			/		

The wind tunnel was used as a chamber to adjust the temperature and humidity. Four ambient temperatures of 15 ℃, 20 ℃, 25 ℃, 30 ℃ and five relative humidity of 40%, 50%, 60%, 70%, 80% were set to get twenty environmental conditions. The experimental system consisting of a droplet generator (YDL-983A, YIDELONG, China), with 34G needle as the nozzle (inside diameter 60 μm), that can generate droplet from diameter 170-200 μm at all tested conditions by air pressure source (0.6 MPa), a UV lamp and a camera (IXUS 105, Canon, Japan). Petri dishes (diameter 9 cm) with 5ml silicone oil inside were used as a collector to collect droplets at the vertical height of 100 cm and 150 cm below the droplet generator's needle (Figure 1). Petri dish was put under a UV lamp in dark condition and imaging was captured by a camera. All Petri dishes were equally divided into three parts. For each part, the volume median diameter (VMD) of droplets was analyzed and calculated by Image J after imaging. The imaging of the ruler was also captured to calibrate. SPSS (version 21.0, IBM, USA) was used to analyze the correlation of different variables.

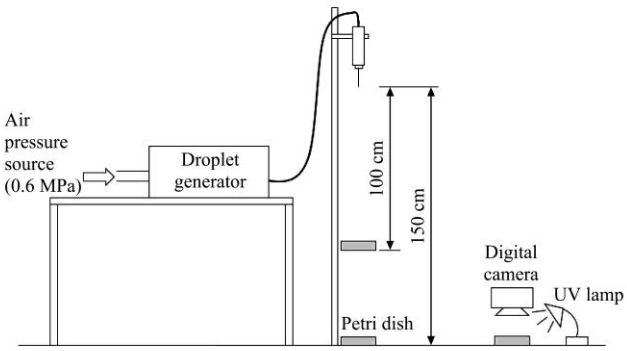
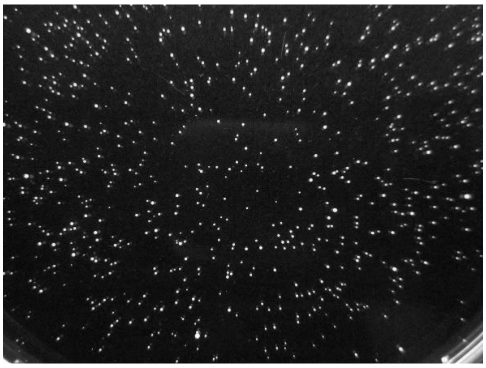
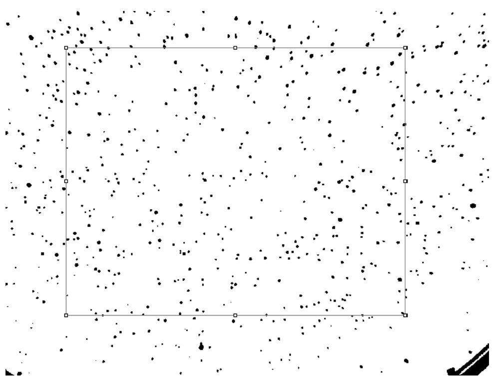


Figure 1 Experimental system used to determine the droplet dynamic evaporation

The original image captured by the camera is shown in Figure 2a, and the image which is used for calculation is shown in Figure 2b. The calculated image is adjusted by setting the threshold is 125 and choosing a certain area ($w \times h$ = 500 – 2800 pix × 300 – 1800 pix) which is shown as the grey rectangle in Figure 2b.



a. Original image



b. Adjusted image

Figure 2 Images of 1.00% Greenwet360 droplets at 25 ℃, *RH* 40% at 100 cm

Three images of each sample in one environment condition and at each height could get 3 VMD, which was used as the droplet size for evaluating droplets evaporation.

3 Results and discussion

3.1 Variation of droplet size

The test height was set at a vertical height of 100 cm and 150 cm below the droplet generator's needle. The reason is that Kincaid's research shows that the velocity of droplets in 0-100 cm decreases rapidly while from around 100 cm the magnitude of the change reduces and the velocity becomes stable[28]. Therefore, 100-150 cm was chosen as a stable-velocity range for testing droplets, where velocity change has less influence on investigating the relationship between ambient temperature, relative humidity, adjuvants and droplets evaporation, which could guarantee the droplets have the same time to evaporate in the air. At 100 cm, the relative standard deviation of the VMD for all adjuvants with 5 concentration at all environment conditions is only 6.9%, which is no significant difference (p=0.133>0.05, Duncan's test).

VMD of all tests is decreasing from 100 to 150 cm, for example, the result of environmental conditions at 20℃ RH 40% is shown in Figure 3. The VMD of all adjuvants at the recommended concentration at 20℃, RH 40% has a significant difference (p=0.000<0.05, Duncan's test) between 2 heights.

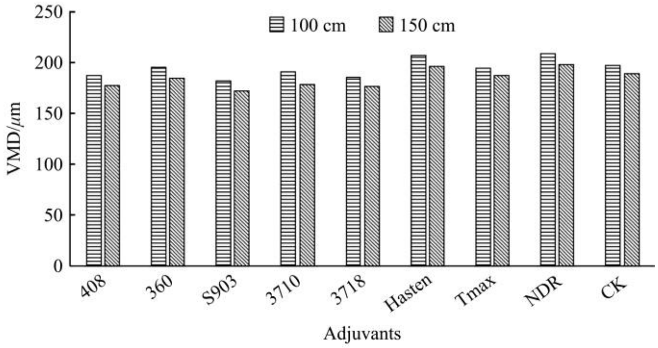


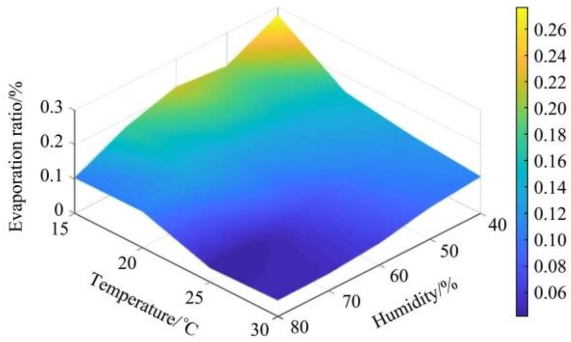
Figure 3 Duncan's multiple range test of VMD at two different heights in 20℃, RH 40%

3.2 Dynamic evaporation and droplet size

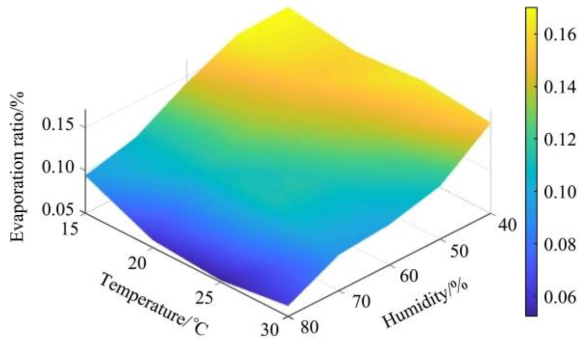
In this study, the dynamic evaporation ratio R_d (%) is used for evaluating evaporation, which is given by:

$$R_d=\frac{\Delta V}{V_0}=\frac{(V_0-V_1)}{V_0}=\frac{(d_0^3-d_1^3)}{d_0^3}$$

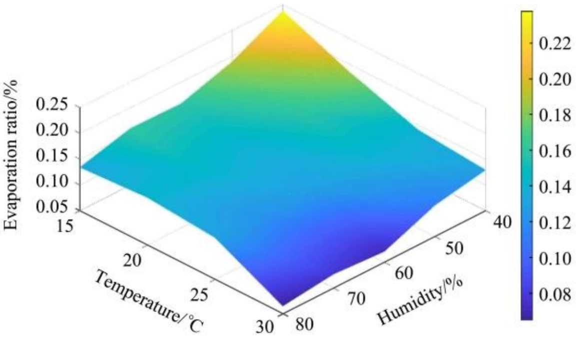
where, ΔV is evaporation quantity, mm^3; V_0, d_0 are the droplet volume (mm^3) and diameter (μm) at 100 cm; V_1, d_1 are the droplet volume (mm^3) and diameter (μm) at 150 cm. The dynamic evaporation ratio of adjuvants with recommended concentrations under different environmental conditions is shown in Figure 4.



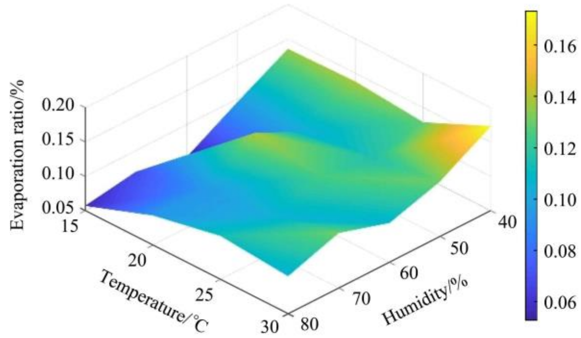
a. Silwet408



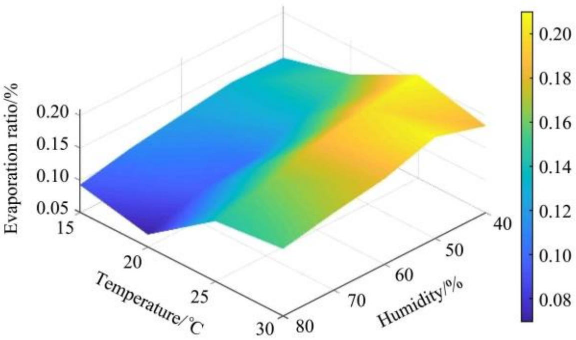
b. S903



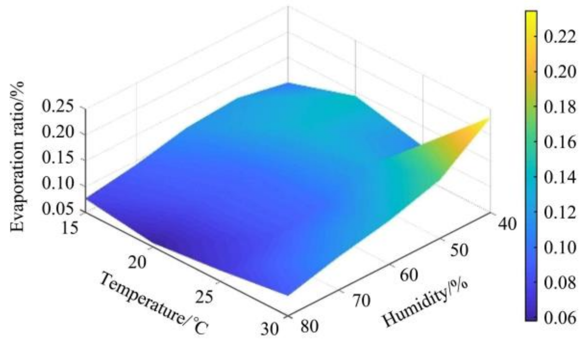
c. Greenwet3710



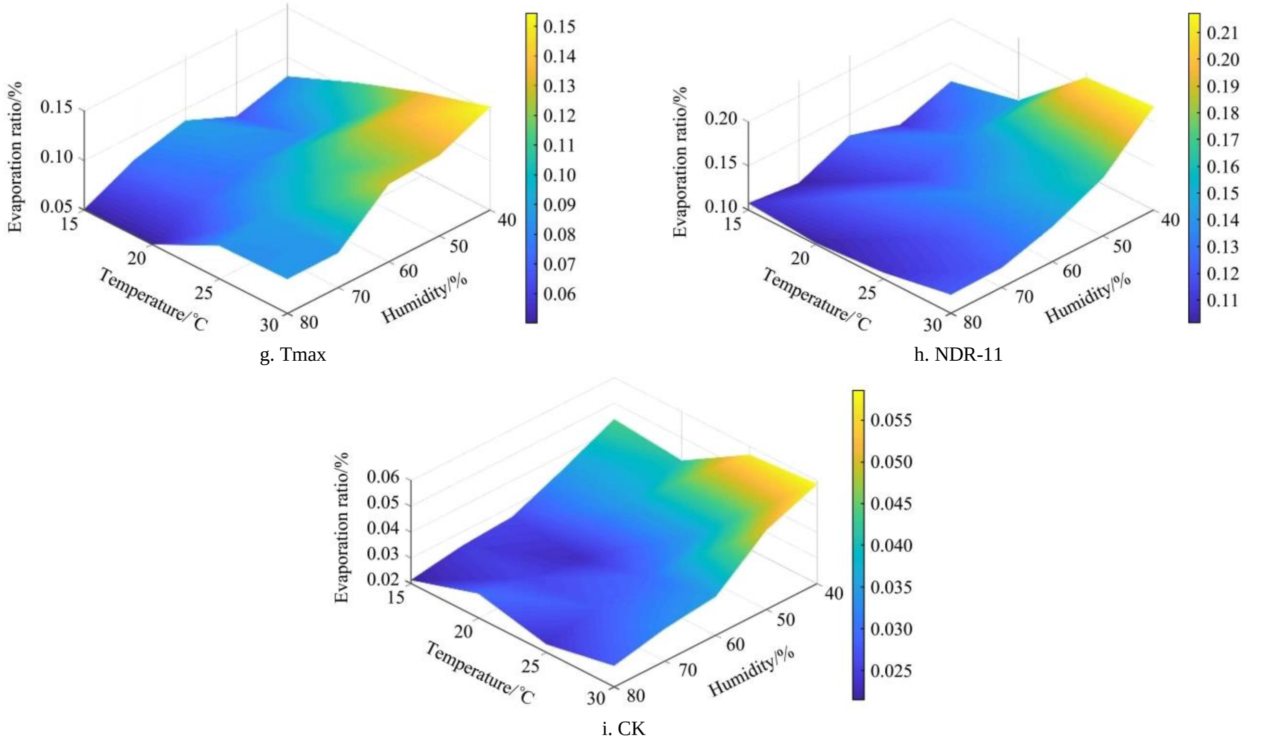
d. Greenwet3718



e. Greenwet360



f. Hasten



g. Tmax

h. NDR-11

i. CK

Figure 4 Dynamic evaporation ratio of adjuvants in different environmental conditions

Ambient temperature and relative humidity has influences on the evaporation ratio of different adjuvants with the same concentration: evaporation ratios of Silwet408, S903 and Greenwet3710 decrease as ambient temperature and relative humidity increases; evaporation ratio of Greenwet360, Greenwet3718, Hasten, Tmax, NDR-11 increases with growing ambient temperature but decreases with rising relative humidity which is consistent with CK; all adjuvants groups have higher evaporation ratio than CK; each adjuvant's evaporation ratio differs with others, e.g. for Silwet408, evaporation ratio is 27.65% at 15 ℃, RH 40% while for S903 evaporation ratio is 17.03%; environmental change also has different impacts on droplet evaporation, e.g. evaporation ratio of Tmax has smoother reduction from 30 ℃, RH 40% to 15 ℃, RH 80% comparing with Hasten. All adjuvants could be separated into 2 types. One is organic-silicon adjuvant, which evaporation ratio is increasing with temperature and humidity increasing; another one is vegetable oil and non-ionic adjuvant, which evaporation ratio is increasing with temperature increasing and humidity decreasing. It means the sprayer could change different types of adjuvant at different ambient conditions.

3.3 Dynamic evaporation and adjuvant concentration

Figure 5 shows the average evaporation ratio of each adjuvant with 5 concentrations under 20 environment conditions. The relationships between dynamic evaporation and different adjuvant concentrations are quite different: concentration of Silwet408 has a negative correlation with evaporation ratio; as the concentration grows, the evaporation of Greenwet360 rises at first and then falls; S903 has the minimum evaporation ratio at the highest concentration (C5) while Greenwet3718 has the maximum one; the evaporation ratio of Greenwet3710 stays in a lower level when in lower concentration (C1, C2) but increases with concentration growing, and so does NDR-11; for Hasten and Tmax, the evaporation ratio Shows unrelated to adjuvant concentration.

Therefore, the effect of concentration on adjuvant is no common regulation for all adjuvants. The evaporation ratio of 3 types adjuvant is no significant difference in the concentration changing, which means the effect of adjuvants concentration needs more research to find the best concentration and regulation. The sprayer is no necessary to change the adjuvants to reduce evaporation.

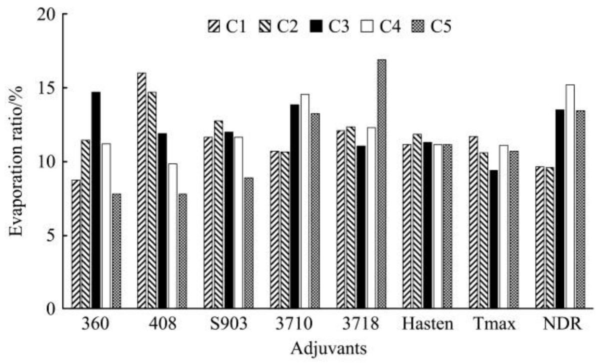


Figure 5 Relationship between dynamic evaporation and adjuvant concentration

3.4 Dynamic evaporation and ambient temperature, relative humidity

The relative humidity is defined as the ratio of water partial pressure to saturation water vapor pressure,

$$RH = \frac{e}{E}$$

where, RH is the relative humidity; E is the saturation water vapor pressure at room temperature, MPa; e is the water vapor pressure, MPa. The water vapor pressure is shown in Table 2.

Evaporation rate is related to evaporation ratio in unit time. According to Dalton evaporation rate[29]:

$$W = C\frac{(E-e)}{P}$$

where, W is the evaporation rate, mg/cm^2 s; P is the atmospheric pressure, MPa; C is a proportional coefficient related to wind speed. As for all the tests that were conducted under no wind conditions, C and P are constant. The difference between saturation water vapor pressure and water vapor pressure (E-e) is shown in Table 3.

Table 2 Water vapor pressure under different temperature and humidity (MPa)

RH	Temperature			
	15℃	20℃	25℃	30℃
40%	0.11	0.16	0.21	0.30
50%	0.29	0.39	0.53	0.76
60%	0.57	0.79	1.06	1.51
70%	0.96	1.31	1.77	2.52
80%	1.36	1.87	2.54	3.60
100% (E)	1.71	2.34	3.17	4.50

Table 3 The difference between saturation water vapor pressure and water vapor pressure (*E*-*e*) (MPa)

RH	Temperature			
	15℃	20℃	25℃	30℃
40%	1.59	2.18	2.96	4.19
50%	1.42	1.95	2.64	3.74
60%	1.13	1.55	2.10	2.98
70%	0.75	1.03	1.39	1.98
80%	0.34	0.47	0.63	0.90

According to the *E* and *E-e* data from (Tables 3 and 4) and Dalton evaporation rate equation that the minimum evaporation rate should be at 15℃ with RH 80% while the maximum one is at 30℃ with RH 40%. It is the same as the variation evaporation ratio of Greenwet360, Greenwet3718, Hasten, Tmax, NDR-11 and CK, except Silwet408, S903, Greenwet3710: the minimum evaporation ratio is at 30℃ with RH 80% and the maximum one comes at 15℃ with RH 40%.

According to correlation analysis (Table 4), Greenwet360, Greenwet3718, Hasten, Tmax, NDR-11 and the CK have a positive correlation with (*E-e*); Silwet408, S903, Greenwet3710, which belong to organo-silicon adjuvant, have a negative correlation with *e*, which infers that evaporation of organo-silicon adjuvant solution has a relationship with water vapor pressure but the evaporation of vegetable oil and non-ionic adjuvant solution were related to the difference between saturation water vapor pressure and water vapor pressure.

However, the reason for the different regulations between organic-silicone, vegetable oil and non-ionic adjuvants is unknown. It may be caused by three types of adjuvants to have different evaporation between the liquid and gas, which also could be caused by different dynamic surface tension, the organic-silicone could achieve balance quickly.

Table 4 Correlation of droplet ratio of adjuvants and (*E*-*e*), e

		Silwet408	Greenwet360	S903	Greenwet3710	Greenwet3718	Hasten	Tmax	NDR	CK
E-e	*r*	–0.099	0.696**	0.170	0.151	0.917**	0.953**	0.953**	0.948**	0.847**
	p-value	0.677	0.001	0.473	0.524	0.000	0.000	0.000	0.000	0.000
e	*r*	–0.689**	0.045	–0.858**	–0.872**	–0.383	–0.392	–0.282	–0.379	–0.238
	p-value	0.001	0.850	0.000	0.000	0.096	0.088	0.229	0.099	0.312

Note: "**" and "*" indicates respectively that the regression model is at a highly significant and significant level.

4 Conclusions

The type of adjuvant, ambient temperature and RH have no significant influence on droplet size generated by droplet generator; evaporation ratio of all the testing groups are larger than the CK which demonstrates that all the adjuvant used in this experiment cannot reduce dynamic evaporation; for different adjuvants, concentration can cause different results of dynamic evaporation which may depend on the property of adjuvant itself; Silwet408, S903, Greenwet3710 which belong to organo-silicon adjuvant have a negative correlation with the water vapor pressure that has less dynamic evaporation at high temperature and RH, and for vegetable oil and non-ionic adjuvant as Greenwet360, Greenwet3718, Hasten, Tmax, NDR-11, the dynamic evaporation reduce with decreasing temperature and increasing RH.

In conclusion, the choice of adjuvant type is very crucial for pesticide applications in different environmental conditions, particularly in UAV spray. Also, it can be inferred that organo-silicon adjuvant should be applied at high temperature and RH for slowing down evaporation while vegetable oil and non-ionic adjuvant are recommended to be the preferred types for low temperature and high RH as they have less evaporation in such condition. The evaporated part of droplets might be water or adjuvant, or mixed evaporation, yet the exact composition in the evaporated part is still unknown waiting for further confirmation.

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