A REVIEW OF THE EFFECTS OF DROPLET SIZE AND FLOW RATE ON THE CHARGEABILITY OF SPRAY DROPLETS IN ELECTROSTATIC AGRICULTURAL SPRAYS

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ABSTRACT. *The chargeability of liquid sprays is an important factor in determining the deposition efficiency of electrostatic pesticide sprays. The Rayleigh limit provides information on the maximum amount of charge a spray droplet can carry as a function of droplet size and liquid properties. This article reviews the literature to determine what fraction of the Rayleigh limit is achievable. Typically, less than 10% of the Rayleigh limit charge is obtained. The droplet charge per unit mass decreases with increasing droplet size and liquid flow rate. A correlation equation is derived from published data to predict spray droplet charge per unit mass from droplet size, flow rate, and charging voltage.*

Keywords. *Droplet size, Electrostatic charging, Spray drift, Sprayers, Ultra-low volume spraying.*

The chargeability of liquid sprays is an important factor in determining the deposition efficiency of electrostatic pesticide sprays. The Rayleigh limit provides information on the maximum amount of charge a spray droplet can carry as a function of droplet size:

$$q_{max} = \sqrt{2} \times 2\pi\sqrt{\varepsilon_o \sigma} \times d^{3/2} \tag{1}$$

where σ is the surface tension (N m^{-1}), d is the diameter of the droplet (m), and ε_o is the permittivity of free space (ε_o = 8.854 × 10^{-12} C^2 N^{-1} m^{-2}). Here d represents an individual spray droplet and not an average diameter for an entire spray cloud. The Rayleigh limit represents the balance between the repulsive electrostatic force trying to pull the droplet apart and the cohesive surface tension force that holds it together. The Rayleigh limit is the relevant limit to droplet charging under conditions seen by agricultural sprayers. The maximum charge per unit mass of spray droplet can be calculated as:

$$\frac{q_{max}}{m} = \frac{\sqrt{2} \times 2\pi\sqrt{\varepsilon_o \sigma} \times d^{3/2}}{\rho \frac{\pi}{6} d^3} = \frac{\sqrt{2} \times 12\sqrt{\varepsilon_o \sigma}}{\rho d^{3/2}} \tag{2}$$

where ρ is the density of the spray liquid (kg m^{-3}). From equation 2 it can be seen that the smaller the droplet size, the greater the charge that can be imparted to the droplet, on a per-mass basis. Law (2014) recommends a charging level on the order of 1 mC kg^{-1} for electrostatic forces to be strong enough to overcome aerodynamic drag and gravity and alter the droplet trajectories to improve deposition. Charging levels of about 10 mC kg^{-1} are the most that is typically seen in field equipment (Law, 2014). As with most theoretical limits, in practice charging levels rarely approach the Rayleigh limit. So what level of charging is realistically achievable with modern electrostatic pesticide spraying equipment?

CHARACTERISTIC DROPLET SIZES

This article reviews the literature to determine what fraction of the Rayleigh limit is achievable. Calculating this fraction requires published values for both spray cloud charge per unit mass and average droplet size simultaneously in the same spray, which is rarely reported. From these data, the fraction (F) of the Rayleigh charging limit can be calculated, as demonstrated by Wilson (1982):

$$F = \frac{1}{6} \times \frac{\rho}{\sqrt{\varepsilon_o \sigma}} \times \frac{q_{act}}{m} \times \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^{1.5}} \tag{3}$$

where n is the total number of droplets in the spray (or a sample of the spray), q_{act}/m is the actual measured charge on the spray cloud per unit spray mass (C kg^{-1}), and d_i is the diameter of each individual spray droplet. This equation requires a summation of the measured droplet size distribution. Most publications report only an average droplet size, typically the volume median diameter (VMD), or $D_{v0.5}$, for agricultural sprays. The summations in equation 3 can be replaced with a properly defined characteristic droplet size:

$$F = \frac{1}{6} \times \frac{\rho}{\sqrt{\varepsilon_o \sigma}} \times \frac{q_{act}}{m} \times (\mathrm{EMD})^{1.5} \tag{4}$$

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where $$\mathrm{EMD} = \left(\frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^{1.5}} \right)^{2/3} \tag{5}$$

This is a new characteristic droplet size, defined for the first time here, and denoted here as an electrostatic-chargeability mean diameter (EMD), or $D_{3,1.5}$. It is similar in form, although not exactly equal to, the Sauter mean diameter (SMD), or D_{32}, which is defined as:

$$\mathrm{SMD} = D_{32} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \tag{6}$$

So a relationship must be found between EMD and VMD. The droplet size data of Nuyttens et al. (2007) for conventional agricultural sprays indicate that the ratio of SMD to VMD falls into a fairly narrow range. Thus, we assume that the ratio of EMD to VMD can be approximated as a constant to engineering accuracy. To find this ratio, measurements of the droplet size distribution from an ESS sprayer were made using a phase-Doppler interferometer (PDI, Artium, Sunnyvale, Cal.). The PDI used the Demeter PDI Probe, which is suitable for outdoor field measurements; this PDI was previously described by Roten et al. (2016). The Demeter PDI Probe uses a 532 nm wavelength with a 300 mm focal length and a 30° collection angle. The static range for droplet size measurement is 3.3 to 547.0 µm, which is suitable for the fine sprays from electrostatic nozzles (typically ASABE classifications Fine, Very Fine, or Extremely Fine). The exact lower limit of droplet size detectability depends on the photo-multiplier tube (PMT) voltage used. For this study, a PMT gain of 500 V was used. For the results shown in figure 1, a 75% data validation rate was obtained. Measurements were made 5 cm from a pneumatic atomizer in combination with induced electrostatic charge spray system (MaxCharge nozzles, Electrostatic Spraying Systems, Watkinsville, Ga.).

From the measured droplet size distribution in figure 1, calculations of the relevant characteristic diameters (VMD, SMD, and EMD) can be made. Also shown for comparison are the number mean diameter (NMD or D_{10}) and the volume mean diameter (D_{30}). As shown in table 1, the EMD is closest in value to the SMD compared to the other commonly used representative diameters, and slightly smaller in magnitude. The relative span (RS) from the distribution shown in figure 1 is 1.46, which is the range of relative spans measured for electrostatic sprays by Martin and Carlton (2013) of 1.36 to 1.66. The relative span is defined as:

$$\mathrm{RS} = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \tag{7}$$

The ratio of EMD to VMD is calculated as 39.6/53.2 = 0.74. Using this ratio now puts us in a position to analyze published measurements from agricultural electrostatic sprays. The assumption is that the droplet size distribution measured from the ESS sprayer will have a similar shape to the droplet size distribution for other electrostatic sprayers, and the ratio of EMD/VMD = 0.74 can be taken as a constant.

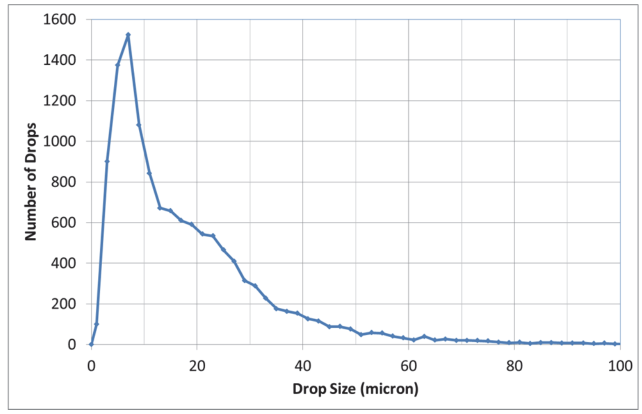

Figure 1. Droplet size distribution from an ESS electrostatic spray nozzle measured using phase-Doppler interferometry.

Table 1. Calculated characteristic droplet sizes from measured ESS droplet size distribution. A sample of 12,641 droplets were measured.

Characteristic Diameter	Value (µm)
D_{10}	17.8
D_{30}	28.6
D_{32}	42.9
VMD	53.2
EMD	39.6

Droplet Size and Charge Measurements

As shown in table 2, only eight publications could be found that reported simultaneous measurements of droplet size and spray charge. Most modern electrostatic sprayers use induction charging, although Ru et al. (2011) used co-

Table 2. Measured spray mass charge, droplet size, voltage, and flow rate from electrostatic agricultural sprays reported in the literature, along with calculated maximum charge.

Reference	Charge, q_{act}/m (mC kg^{-1})	Droplet Size, VMD (µm)	Charging Voltage (kV)	Liquid Flow Rate per Nozzle (L min^{-1})	Rayleigh Limit, q_{max}/m (mC kg^{-1})	Fraction of Rayleigh Limit Obtained (F)
Marchant and Green (1982)	1.31	155	6.0	0.17	11.0	11.9%
Gan-Mor et al. (2014)	1.85	115	10.5	0.45	17.3	10.7%
Ru et al. (2011)	2.35	81	20.0	0.67	29.3	8.0%
Scherm et al. (2007)	7.80	30	1.1	Not given	129	6.0%
Martin and Carlton (2013)[a]	1.63, 0.89	85, 92	6.0, 6.0	0.42, 0.85	27.2, 24.1	6.0%, 3.7%
Moon et al. (2003)	2.10	65	3.0	0.75	40.6	5.2%
Jia et al. (2015)	1.00	84	4.0	0.33[b]	27.6	3.6%
Laryea and No (2003)	0.37	113	5.0	0.69	17.7	2.1%

[a] Martin and Carlton (2013) reported data for 20 trials. The maximum and minimum F values are shown here.
[b] Flow rate estimated from nozzle size and pressure.

rona charging. Most authors did not report the properties of the liquid they used, and some did not even report which liquid they used. If the liquid properties were not given, the surface tension of tap water was assumed. If the mixture had a lower surface tension than tap water, the fraction of the Rayleigh limit achieved would be higher. Additionally, Wilson (1982) and Western et al. (1994) were not included in table 1 because they used slot injectors that are not representative of field equipment. Patel et al. (2017) was also not included because their droplet size measurements were estimated from splatter sizes collected on paper samplers and had considerable uncertainty.

Maski and Durairaj (2010) found that the liquid flow rate has a strong effect on the chargeability of droplets. Unfortunately, very few authors reported measured flow rate, along with simultaneously measured droplet size and spray charge. A further complicating factor is that increasing the flow rate typically decreases the droplet size in aerodynamic atomization processes. Thus, it is not possible to quantitatively assess the effect of increasing flow rate (or supply pressure) on spray chargeability independent of the droplet size from the currently published data. Increasing the flow rate decreases the spray charge because there is less residence time for the droplets in the induction charging zone to accumulate charge. Maski and Durairaj (2010), Kacprzyk and Lewandowski (2016), Maynagh et al. (2009), and Frost and Law (1981) measured spray charge for multiple flow rates, and they all found that increasing the liquid flow rate (L min^{-1}) decreased the spray mass charge (mC kg^{-1}). The only counter-example that could be found was Laryea and No (2003), who reported an increase in charge to mass ratio with liquid flow rate. At higher liquid flow rates, they also reported smaller droplet sizes, which increased the charging. They also used a pressure-swirl nozzle that is different from the other nozzles reviewed, so nozzle design also affects the chargeability of the sprays.

Effects of Flow Rate on Droplet Charge

Figure 2 shows a compilation of measured droplet charge as a function of liquid flow rate from the literature. To normalize the spray charge per mass (mC kg^{-1}) across different equipment and test conditions, it is divided by the charging voltage used (kV). This is equivalent to the slope of the charging curve when varying the electrode voltage. Most studies of voltage showed a linear increase in droplet charge with voltage, up to some maximum. The data in figure 2 were compiled from various sources, listed in table 3, and were not controlled for droplet size (most references did not report droplet size). In most atomization models for hydraulic nozzles, droplet size varies inversely with flow rate (Lefebvre, 1989), although the co-flowing air-assistance commonly used for electrostatic sprayers further complicates the atomization process. Overall in figure 2, there is a clear trend of decreasing normalized droplet charge with increasing flow rate, although it is not clear how concurrent changes in droplet size might affect the curve.

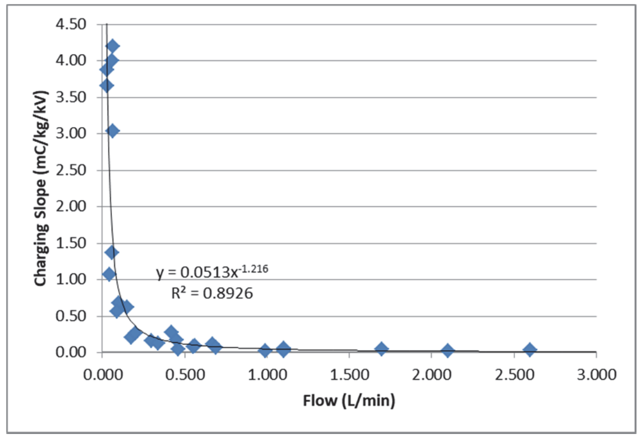

Figure 2. Effect of liquid flow rate on the charging slope of electrostatic sprayers. Charging slope is the spray charge per unit mass (mC kg^{-1}) normalized by the charging voltage used (kV) at that data point. Data not controlled for droplet size. Compiled from references in table 3.

The only study found that reported reliable measurements of droplet size, flow rate, and spray charge simultaneously was that of Martin and Carlton (2013). This was a wind tunnel study in which the wind speed changed, which changed the atomized droplet size without changing the flow rate. The fraction of the Rayleigh limit obtained (F) versus flow rate for all 20 measured conditions is shown in figure 3. A clear trend of decreasing chargeability with increasing flow rate is seen. Figure 4 shows F as a function of droplet size. No clear trend is seen, and the range of F is fairly narrow, from 3.9% to 6.0% with an average of 4.6%, indicating that scaling of the Rayleigh limit dominates droplet size effects.

However, when the droplet charge is normalized with charging voltage, as shown in figure 5, there is a clear trend of decreasing charging slope with increasing droplet size. Force-fitting a power law curve with an exponent of -1.5, following the Rayleigh limit scaling, gives a regression

Table 3. Summary of literature reporting spray charge versus charging voltage trends and liquid flow rates.

Reference	Charge, q_{act}/m (mC kg^{-1})	Charging Voltage (kV)	Charging Slope (mC kg^{-1} kV^{-1})	Liquid Flow Rate per Nozzle (L min^{-1})
Patel et al. 2015	10.50	2.5	4.20	0.06
Frost and Law (1981)[a]	8.00	2.0	4.00	0.06
Maski and Durairaj (2010)[a]	15.50	4.0	3.90	0.03
Franz et al. (1987)	9.10	3.0	3.00	0.07
Kacprzyk and Lewandowski (2016)[a]	3.20	12.0	0.27	0.20
Martin and Carlton (2013)[a]	1.63	6.0	0.27	0.42
Marchant and Green (1982)	1.31	6.0	0.21	0.17
Gan-Mor et al. (2014)	1.85	10.5	0.18	0.45
Mamidi et al. (2013)	0.42	3.2	0.13	0.34
Ru et al. (2011)	2.35	20.0	0.12	0.67
Laryea and No (2003)	0.37	5.0	0.07	0.69
Yamane and Miyazaki (2017)[a]	0.23	6.0	0.04	2.60

[a] References that measured droplet charge for multiple flow rates. For readability, only one condition is shown in the table.

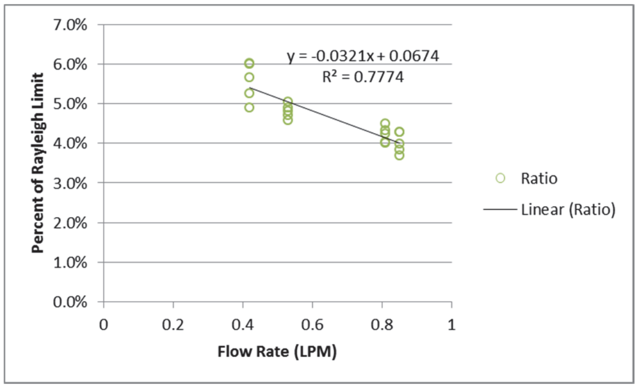

Figure 3. Fraction of Rayleigh limit obtained (*F*) calculated using equation 4 as a function of liquid flow rate from the data of Martin and Carlton (2013).

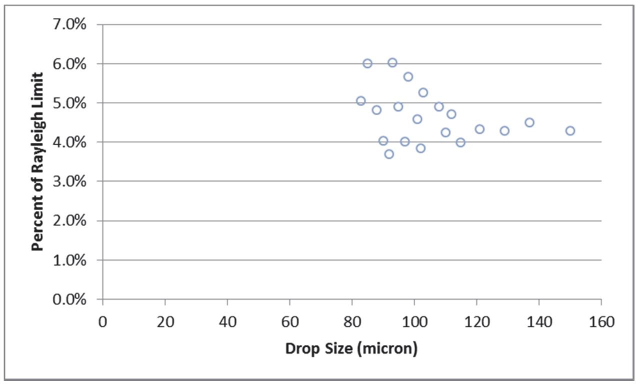

Figure 4. Fraction of Rayleigh limit obtained (*F*) calculated using equation 4 as a function of average droplet size (VMD) from the data of Martin and Carlton (2013).

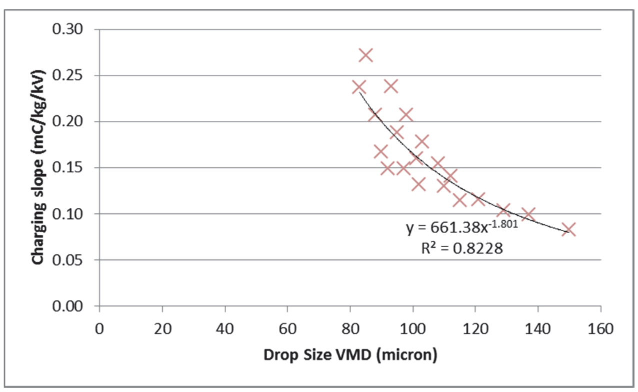

Figure 5. Calculated values of normalized charging slope (charge per mass divided by charging voltage used) as a function of average spray droplet size (VMD) from the data of Martin and Carlton (2013).

equation with $R^2 = 0.74$:

$$(q/m\ \text{kV}^{-1}) = 169 \times \text{VMD}^{-1.5} \qquad (11)$$

Statistical analysis of the data from Martin and Carlton (2013) was also undertaken to analyze the significance of trends in droplet charge as a function of both flow rate and droplet size. *F* is the ratio of actual charge to the Rayleigh limit. The model used in deriving table 4 is the Rayleigh limit equation for trends in droplet charge versus droplet size. In the last column of table 4, the same letter in different rows indicates that there is no significant difference between

Table 4. Statistical analysis of data of Martin and Carlton (2013).

Droplet Size (VMD, µm)	Flow Rate (L min^{-1})	*F* (mean)	Significance (see text)
50	0.42	0.02092	fg
	0.53	0.01857	g
	0.81	0.01316	g
	0.85	0.01158	g
100	0.42	0.05916	de
	0.53	0.05252	def
	0.81	0.03724	defg
	0.85	0.03276	efg
150	0.42	0.10500	b
	0.53	0.10100	b
	0.81	0.06841	cd
	0.85	0.06019	de
200	0.42	0.16730	a
	0.53	0.14860	a
	0.81	0.10530	c
	0.85	0.09267	bc

the data points, thus demonstrating that increasing flow rate decreases the chargeability of spray droplets independent of droplet size. As shown in table 4, the effects of flow rate on chargeability are more pronounced at larger droplet sizes.

CORRELATIONS

To further investigate the relationships between droplet charge, droplet size, and liquid flow rate in the data of Martin and Carlton (2013), a multivariate power-law regression was performed, which required the use of a logarithmic transformation. The initial correlation resulted in:

$$(q/m\ \text{V}^{-1}) = 77.45 \times (\text{L min}^{-1})^{-0.4534}(\text{VMD})^{-1.3853} \qquad (9)$$

$$(R^2 = 0.965)$$

This correlation is for scaled droplet charge (q/m V^{-1}) in units of mC kg^{-1} kV^{-1} and droplet size (VMD) in units of microns. Forcing the exponent of droplet size to -1.5 yields:

$$(q/m\ \text{V}^{-1}) = 134.0 \times (\text{L min}^{-1})^{-0.4239}(\text{VMD})^{-1.50} \qquad (10)$$

$$(R^2 = 0.963)$$

Finally, forcing the exponent of flow rate to -0.5 yields:

$$(q/m\ \text{V}^{-1}) = 129.1 \times (\text{L min}^{-1})^{-0.50}(\text{VMD})^{-1.50} \qquad (11)$$

$$(R^2 = 0.957)$$

This correlation can be applied to the other references in table 2, as shown in table 5. The model fits the data from the literature reasonably well, with the exception of Moon et al. (2003), who used a pulse-capacitive charging system with a swirl nozzle, which is different from the systems used by most other authors.

Figure 6 shows a plot of droplet charge per unit mass (q/m) at 5% and 10% of the Rayleigh limit versus droplet size for water. The range of 5% to 10% was chosen as representative of typical agricultural sprayers, based on table 2. Thus, obtaining the minimum of 1 mC kg^{-1} charge recommended by Law (2014) requires a VMD no greater than 165 µm, and the maximum charge of 10 mC kg^{-1} typically seen in agricultural sprayers can be obtained with a VMD of 36 µm at 10% of the Rayleigh limit. The corresponding VMD values at 5% of the Rayleigh limit are 104 µm and 22 µm, respectively.

Table 5. Comparison of electrostatic spray charging slope with regression model from data of Martin and Carlton (2013).

Reference	Charge, q_{act}/m (mC kg^{-1})	Charging Voltage (kV)	Droplet Size (VMD, µm)	Flow Rate per Nozzle (L min^{-1})	Charging Slope (mC kg^{-1} kV^{-1})	Model (eq. 10) (mC kg^{-1} kV^{-1})
Moon et al. (2003)	2.10	3.0	65	0.75	0.70	0.28
Jia et al. (2015)	1.00	4.0	84	0.33	0.25	0.29
Marchant and Green (1982)	1.31	6.0	155	0.17	0.22	0.16
Gan-Mor et al. (2014)	1.85	10.5	115	0.45	0.18	0.16
Ru et al. (2011)	2.35	20.0	81	0.67	0.12	0.22
Laryea and No (2003)	0.37	5.0	113	0.69	0.07	0.12

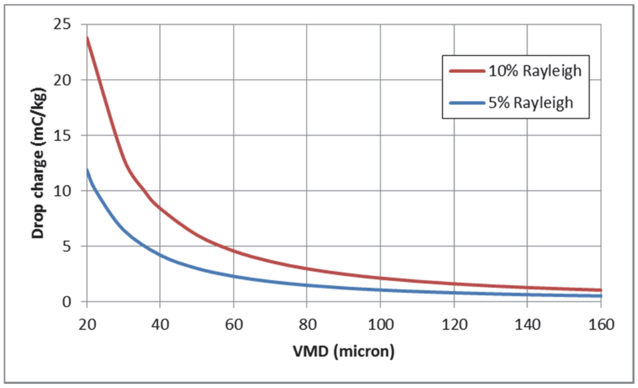

Figure 6. Calculated droplet charge as a function of VMD using equation 10 and assuming 5% and 10% of the Rayleigh limit is obtained.

Conclusion

Based on a review of the published literature on electrostatic agricultural spraying, it was found that charging to 5% to 10% of the Rayleigh limit is typical for modern electrostatic sprayers, although some sprayers achieve even less than this. It is important that simulations, computational fluid dynamics (CFD), and theoretical studies use realistic values of charging that are an order of magnitude less than the Rayleigh limit. Droplet charge per mass can be increased by increasing the voltage, decreasing the droplet size, or reducing the flow rate per nozzle. The challenges for practical application are that decreasing the droplet size increases the risk of drift, and reducing the flow rate reduces the maximum amount of chemical that can be applied; otherwise, more nozzles must be added to compensate.

Equation 10 can be used to select design parameters to obtain a spray charge of 1.0 mC kg^{-1} or greater, as recommended by Law (2014) for enhancing deposition. For example, for a charging voltage of 1.0 kV and a droplet size (VMD) of 100 µm, the flow rate should be no more than 0.016 L min^{-1} per nozzle.

Previous reviews (Matthews, 1989; Law, 2001; Patel, 2016) of electrostatic spraying equipment for agriculture have focused on the hardware options and performance in the field. This is the first review to analyze and quantify the effects of droplet size and flow rate on the chargeability of electrostatic sprays. This understanding is critical to the design of future systems to maximize in-field performance.

The lack of droplet size data for electrostatic sprayers as a function of liquid supply pressure, nozzle size, airflow rate, and charging voltage is a limitation to further theoretical development.

References

Franz, E., Reichard, D. L., Carpenter, T. G., & Brazee, R. D. (1987). Deposition and effectiveness of charged sprays for pest control. *Trans. ASAE, 30*(1), 50-55. https://doi.org/10.13031/2013.30400

Frost, A. R., & Law, S. E. (1981). Extended flow characteristics of the embedded-electrode spray-charging nozzle. *J. Agric. Eng. Res., 26*(1), 79-86. https://doi.org/10.1016/0021-8634(81)90128-1

Gan-Mor, S., Ronen, B., & Ohaliav, K. (2014). The effect of air velocity and proximity on the charging of sprays from conventional hydraulic nozzles. *Biosyst. Eng., 121*, 200-208. https://doi.org/10.1016/j.biosystemseng.2014.03.004

Jia, W., Hu, H., Chen, L., Chen, Z., & Wei, X. (2015). Performance experiment on spray atomization and droplets deposition of wind-curtain electrostatic boom spray. *Trans. Chinese Soc. Agric. Eng., 31*(7), 53-59.

Kacprzyk, R., & Lewandowski, M. (2016). Post-dispersion electrification of droplets. *J. Electrostat., 79*, 33-37. https://doi.org/10.1016/j.elstat.2015.12.001

Laryea, G. N., & No, S. Y. (2003). Development of electrostatic pressure-swirl nozzle for agricultural applications. *J. Electrostat., 57*(2), 129-142. https://doi.org/10.1016/S0304-3886(02)00122-5

Law, E. (2014). Chapter 10: Electrostatically charged sprays. In G. A. Matthews (Ed.), *Pesticide application methods* (4th ed., pp. 275-298). Oxford, UK: Wiley. https://doi.org/10.1002/9781118351284.ch10

Law, S. E. (2001). Agricultural electrostatic spray application: A review of significant research and development during the 20th century. *J. Electrostat., 51*, 25-42.

Lefebvre, A. H. (1989). *Atomization and sprays.* New York, NY: Hemisphere Publishing.

Mamidi, V. R., Ghanshyam, C., Kumar, P. M., & Kapur, P. (2013). Electrostatic hand-pressure knapsack spray system with enhanced performance for small-scale farms. *J. Electrostat., 71*(4), 785-790. https://doi.org/10.1016/j.elstat.2013.01.011

Marchant, J. A., & Green, R. (1982). An electrostatic charging system for hydraulic spray nozzles. *J. Agric. Eng. Res., 27*(4), 309-319. https://doi.org/10.1016/0021-8634(82)90070-1

Martin, D. E., & Carlton, J. B. (2013). Airspeed and orifice size affect spray droplet spectrum from an aerial electrostatic nozzle for fixed-wing applications. *Appl. Eng. Agric., 29*(1), 5-10. https://doi.org/10.13031/2013.42528

Maski, D., & Durairaj, D. (2010). Effects of electrode voltage, liquid flow rate, and liquid properties on spray chargeability of an air-assisted electrostatic-induction spray-charging system. *J. Electrostat., 68*(2), 152-158. https://doi.org/10.1016/j.elstat.2009.12.001

Matthews, G. A. (1989). Elestrostatic spraying of pesticides: A review. *Crop Prot., 8*(1), 3-15. https://doi.org/10.1016/0261-2194(89)90093-8

Maynagh, B. M., Ghobadian, B., Jahannama, M. R., & Hashjin, T. T. (2009). Effect of electrostatic induction parameters on droplets charging for agricultural application. *J. Agric. Sci.*

Tech., 11(3), 249-257.
Moon, J. D., Lee, D. H., Kang, T. G., & Yon, K. S. (2003). A capacitive type of electrostatic spraying nozzle. *J. Electrostat., 57*(3-4), 363-379. https://doi.org/10.1016/S0304-3886(02)00173-0
Nuyttens, D., Baetens, K., De Schampheleire, M., & Sonck, B. (2007). Effect of nozzle type, size, and pressure on spray droplet characteristics. *Biosyst. Eng., 97*(3), 333-345. https://doi.org/10.1016/j.biosystemseng.2007.03.001
Patel, M. K. (2016). Technological improvements in electrostatic spraying and its impact to agriculture during the last decade and future research perspectives: A review. *Eng. Agric. Environ. Food, 9*(1), 92-100. https://doi.org/10.1016/j.eaef.2015.09.006
Patel, M. K., Praveen, B., Sahoo, H. K., Patel, B., Kumar, A., Singh, M., ... Rajan, P. (2017). An advance air-induced air-assisted electrostatic nozzle with enhanced performance. *Comput. Electron. Agric., 135*, 280-288. https://doi.org/10.1016/j.compag.2017.02.010
Patel, M. K., Sahoo, H. K., Nayak, M. K., Kumar, A., Ghanshyam, C., & Kumar, A. (2015). Electrostatic nozzle: New trends in agricultural pesticides spraying. *SSRG Intl. J. Electr. Electron. Eng.*, April 2015. Retrieved from http://maxcharge.com/Articles/SSRG-IJEEE%20April%202015%20Electrostatic%20Nozzle%20India%20Ag%20improvements.pdf
Roten, R. L., Post, S. L., Werner, A., Hewitt, A. J., & Safa, M. (2016). Volumetric validation of mass balance using a computational phase Doppler approach for disc core nozzles. *Crop Prot., 79*, 128-134. https://doi.org/10.1016/j.cropro.2015.10.018
Ru, Y., Zhou, H., & Zheng, J. (2011). Design and experiments on droplet charging device for high-range electrostatic sprayer. In *Pesticides in the modern world-pesticides use and management.* Rijeka, Croatia: InTech. https://doi.org/10.5772/18546
Scherm, H., Savelle, A. T., & Law, S. E. (2007). Effect of electrostatic spray parameters on the viability of two bacterial biocontrol agents and their deposition on blueberry flower stigmas. *Biocontrol Sci. Tech., 17*(3), 285-293. https://doi.org/10.1080/09583150701211616
Western, N. M., Hislop, E. C., & Dalton, W. J. (1994). Experimental air-assisted electrohydrodynamic spraying. *Crop Prot., 13*(3), 179-188. https://doi.org/10.1016/0261-2194(94)90076-0
Wilson, J. M. (1982). A linear source of electrostatically charged spray. *J. Agric. Eng. Res., 27*(4), 355-362. https://doi.org/10.1016/0021-8634(82)90074-9
Yamane, S., & Miyazaki, M. (2017). Study on electrostatic pesticide spraying system for low-concentration, high-volume applications. *Japan Agric. Res. Qtly., 51*(1), 11-16. https://doi.org/10.6090/jarq.51.11