EDITORIAL CSIC

Spanish Journal of Agricultural Research
24 (1) January-March 2026, 21696
ISSN-L: 1695-971X, eISSN: 2171-9292
https://doi.org/10.5424/sjar/2026241-21696

ARTICLE

REVIEW ARTICLE

Charge-to-mass ratio measurement in agricultural electrostatic spraying: critical review and design insights

Medición de la relación carga-masa en la pulverización electrostática agrícola: revisión crítica y consideraciones de diseño

Kemal Amaya
Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, Çukurova University. 01330 Adana, Türkiye
Corresponding author: kemal.amaya86@gmail.com, https://orcid.org/0000-0002-5096-1585

Ali Bayat
Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, Çukurova University. 01330 Adana, Türkiye
alibayat@cu.edu.tr, https://orcid.org/0000-0002-7104-9544

Abstract: Electrostatic spraying technology has gained significant attention due to its potential to enhance droplet deposition, improve coverage uniformity, and reduce pesticide waste. Accurate evaluation of charging efficiency using standardized apparatuses is essential for optimizing electrostatic spraying systems and enabling consistent comparisons across different studies. This review systematically explores methodologies for measuring the charge-to-mass ratio, with a particular focus on Faraday cages and conductive plates. Key design considerations, such as material selection, geometric configuration, insulation from external influences, and measurement sensitivity, are discussed for their impact on measurement accuracy and reliability. By analyzing these factors, this review contributes to the development of a standardized charge-to-mass ratio measurement system, promoting consistency in evaluating electrostatic spraying technologies. Its novelty lies in the comparative evaluation of existing techniques and the identification of critical parameters influencing measurement reliability. Additionally, this review serves as a practical resource for researchers, especially newcomers, providing guidance on designing and evaluating electrostatic charging systems without requiring extensive experimentation.

Keywords: Charge-to-mass ratio; charging efficiency of spray droplets; contact charging; electrostatic spraying technology; Faraday cage; induction charging.

Resumen: La tecnología de pulverización electrostática ha despertado un interés considerable debido a su potencial para mejorar la deposición de gotas, aumentar la uniformidad de la cobertura y reducir el desperdicio de pesticidas. La evaluación precisa de la eficiencia de carga mediante dispositivos de medición estandarizados es esencial para optimizar los sistemas de pulverización electrostática y permitir comparaciones coherentes entre diferentes estudios. Esta revisión explora de manera sistemática las metodologías utilizadas para medir la relación carga-masa, con especial énfasis en las jaulas de Faraday y las placas conductoras. Se analizan los principales criterios de diseño, como la selección de materiales, la configuración geométrica, el aislamiento frente a influencias externas y la sensibilidad de medición, debido a su impacto en la exactitud y fiabilidad de las mediciones. A través del análisis de estos factores, esta revisión contribuye al desarrollo de un sistema estandarizado para la medición de la relación carga-masa, promoviendo la coherencia en la evaluación de las tecnologías de pulverización electrostática. La novedad de este trabajo radica en la evaluación comparativa de las técnicas existentes y en la identificación de los parámetros críticos que influyen en la fiabilidad de las mediciones. Además, esta revisión constituye un recurso práctico para los investigadores, especialmente para aquellos que se inician en el área, al proporcionar directrices para el diseño y la evaluación de sistemas de carga electrostática sin necesidad de realizar experimentación exhaustiva.

Palabras clave: carga por contacto; carga por inducción; eficiencia de carga de gotas pulverizadas; jaula de Faraday; relación carga-masa; tecnología de pulverización electrostática.

Received: 18-03-2025 / **Accepted**: 13-10-2025 / **Published**: 16-06-2026

Citation: Amaya, K; Bayat, A (2026). Charge-to-mass ratio measurement in agricultural electrostatic spraying: critical review and design insights. *Spanish Journal of Agricultural Research*, Volume 24, Issue 1, 21696. https://doi.org/10.5424/sjar/2026241-21696

Supplementary information ↓

1. INTRODUCTION

The increasing prevalence of plant diseases and fungal pathogens has escalated the demand for effective pesticide applications. While chemical treatments are essential for disease control, their overuse leads to higher chemical residues on crops and environmental contamination of soil and water (Blettler *et al.*, 2022; Kayim *et al.*, 2022; Durairaj & Jyoti, 2023; Garcia *et al.*, 2024; Almourrh *et al.*, 2024, 2025; Alsalmo *et al.*, 2025).

Hu *et al.* (2022) reported that activating the electrostatic charge increased droplet deposition by 31% and reduced drift by 39%. Similarly, Zhao *et al.* (2024) found that electrostatic charging nozzles increased droplet deposition by 187% and the density by 131%. Electrostatic charging of spray droplets also improves deposition in hard-to-reach areas, such as the back surfaces of plant leaves. Amaya & Bayat (2024a) reported an increase in the droplet deposition of 54% on the front and 112% on the back surfaces compared with uncharged standard spraying. This increase in droplet deposition can directly enhance biological control. For instance, Cunha *et al.* (2017) demonstrated that electrostatic spray technology improved biological control by 90% compared to traditional spray applications.

Electrostatic spraying technology charges droplets using three primary methods: corona, contact, and induction charging. These methods influence deposition efficiency primarily through Coulombic attraction forces, which govern the electrostatic interaction between droplets and plant surfaces according to Coulomb's law:

$$F = k.\frac{q_1 \cdot q_2}{r^2} \qquad (1)$$

Where F (N) is the electrostatic force, k (8.99 x 109 $N·m^2/C^2$) is Coulomb´s constant, q1 and q2 (C) are the charges of the droplet and the plant target, and r (m) is the distance between them.

The charge-to-mass ratio (CMR, mC/kg) is a key metric representing the electric charge per unit mass of spray liquid. Higher CMR values enhance droplet attraction to plant surfaces, improving coverage and reducing drift (Figure 1). Effective electrostatic deposition depends on charging droplets sufficiently to overcome opposing forces such as gravity and air drag.

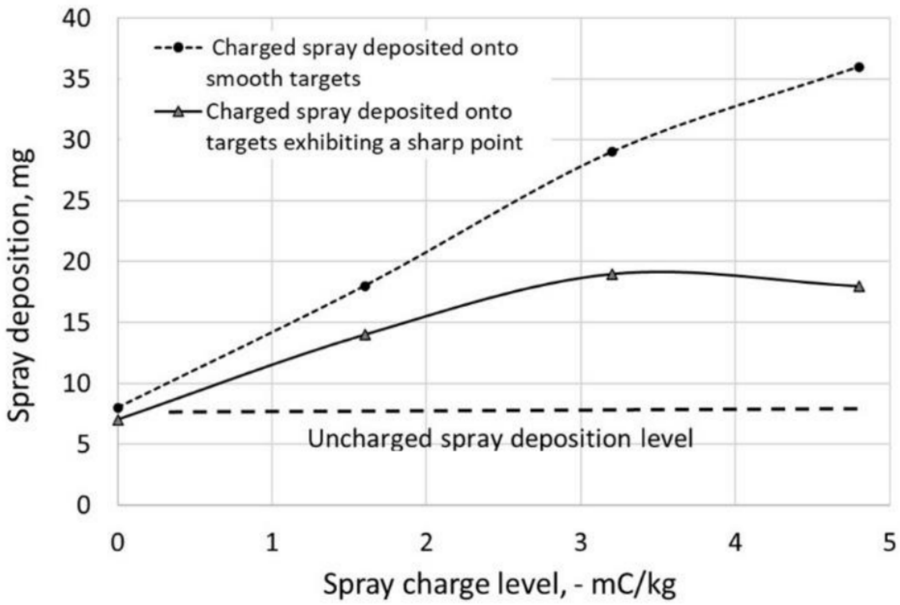

Figure 1. Effect of CMR values on spray deposition (Law & Cooper, 2024).

Accurate CMR measurement is essential for optimizing electrostatic spraying systems. Measurement techniques are classified as static and dynamic. The static method, most commonly using Faraday cages or conductive plates, evaluates the charge of the entire spray and is widely preferred due to its simplicity and cost-effectiveness. The CMR (mC/kg) is calculated as:

$$\mathrm{CMR} = \frac{\mathrm{I_s}}{\mathrm{Q_m}} \qquad (2)$$

Where I_s(μA) is the measured spray current, and Q_m(g/s) is the liquid mass flow rate.

Despite extensive research, no standardized Faraday cage or conductive plate design exists, leading to variability in measurement accuracy across studies. This variability arises from differences in experimental parameters such as nozzle type, liquid flow rate, applied voltage, airflow conditions, and cage geometry across studies. For example, low-flow air-assisted electrostatic nozzles use compact cages, while high-flow hydraulic systems require robust designs to manage the resulting turbulence, especially when airflow is used to prevent electrode wetting. Field electrostatic sprayers also demand specific configurations to account for large-scale application conditions.

This review critically examines static CMR measurement methods for agricultural electrostatic spraying, focusing on Faraday cage and conductive plate designs. By identifying key factors influencing measurement accuracy and outlining best practices, it aims to support the optimization of electrostatic spraying systems, facilitating precise, efficient, and environmentally sustainable pesticide applications.

2. METHODOLOGY

This systematic review is carried out following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 (Page *et al.*, 2021a, 2021b). The purpose was to find out and study static methods to estimate the CMR in agricultural electrostatic spray systems by answering three important research questions:

(Q1) What are the static measurement techniques employed for determining CMR?

(Q2) What is the effectiveness of the existing assessment methods?

(Q3) What are the most important design specifications of this evaluation equipment?

This review determines the equipment used to answer the first question (Q1) and uses a structured framework to determine the effectiveness and required design specifications of the evaluation techniques (Q2 and Q3).

2.1. Search strategy and eligibility criteria

A comprehensive literature search was conducted using Scopus and Web of Science databases for studies published up to 2025. The search strategy employed a combination of keywords and Boolean operators, applied to the title, abstract, and keywords fields. The search string used was: (“Faraday cage to evaluate charging efficiency of spray droplets” OR “conductive plate to evaluate charging efficiency of spray droplets”) AND (“Electrostatic agricultural spraying” OR “Charge-to-mass ratio of spray droplets” OR “Electrostatic spray charging systems”)

This approach ensured that only relevant studies focusing on the evaluation of CMR in electrostatic agricultural spraying were included. Duplicate records were removed, and only peer-reviewed journal articles indexed in Scopus or Web of Science were considered, enhancing the reliability and reproducibility of the review. As a result, the analysis was completed with 23 records, out of which there were 110 initial records.

2.2. Data extraction and evaluation framework

The spray charging systems vary widely in both design and operational parameters, making direct quantitative comparison unfeasible. To address this heterogeneity, a formalized descriptive analysis framework was established. The evaluation criteria outlined in Table 1 were applied to each Faraday cage design, enabling a more systematic appraisal of their respective limitations and clarifying the direction for future standardization efforts. The “Operational Stability” criterion was not applied to air-assisted electrostatic nozzles, as these systems generally operate at low flow rates and without external airflow that could impact stability.

Table 1. Criteria for systematic evaluation of measurement equipment of CMR

NO	Criterion	Description	Scoring
1	Geometrical design	Assesses if the design is appropriate for evaluating the CMR and if its engineering specifications (e.g., structure, mesh layers) are clearly defined.	1 mark for a suitable and well-designed device.
2	Environmental isolation	Determines if the design effectively shields droplets from external influences that could dissipate their charge before measurement.	1 mark for isolation.
3*	Operational stability	Assess if the design is robust enough for experiments involving external airflow and high liquid flow rates common in electrostatic systems designed using hydraulic nozzles.	1 mark for a design suitable for external airflow
4	Ammeter accuracy	Evaluates the accuracy and sensitivity of the used ammeter at 0.5 µA, as reliability is critical when measuring such low currents, which are typical in these charging experiments.	1 mark for error ≤5%; 0.5 marks for error between 5-10% or if the model is unclear; 0 marks for error >10%.

***** Only for electrostatic charging systems based on hydraulic nozzles, CMR: charge-to-mass ratio

3. STATIC EQUIPMENT FOR CMR EVALUATION (Q1)

3.1. Faraday cage

Figure 2 shows the schematic design of the Faraday cage, highlighting components critical for accurate charge measurement. The system consists of a conductive mesh enclosed within a housing (e.g., a pail) that intercepts charged droplets and collects their electric charge. It is mounted on an insulating support to prevent electrical leakage to ground, ensuring the measured current originates solely from the charged droplets. In some configurations, an external insulating layer is added to shield the cage from external interference or nearby conductive objects that could cause charge dissipation and reduce accuracy. A sensitive ammeter, connected between the mesh and ground, is used to detect the induced current in the microampere (µA) range. As charged droplets pass through the mesh, their electrical charge is transferred, generating a current that flows to ground through the ammeter. This current is recorded with high resolution, enabling precise calculation of the CMR according to equation (2).

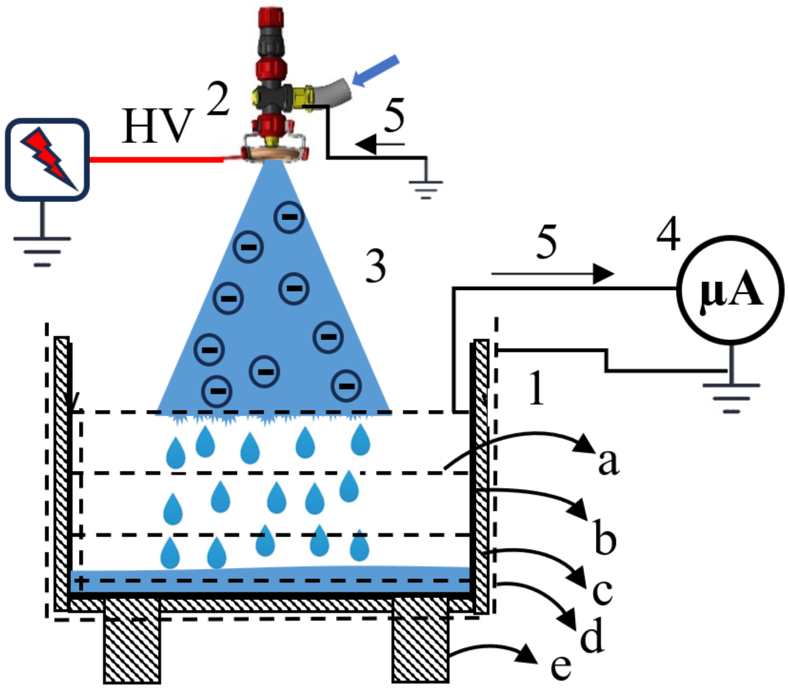

Figure 2. General design of Faraday cage for measuring the electric current of charged droplets: 1–Faraday cage (a–Conductive mesh, b–Mesh housing, c–Insulating layer, d–Grounded outer insulation layer, e–Insulating supports from ground); 2–Electrostatic nozzle; 3–Charged droplets; 4–Sensitive ammeter; 5–Direction of electric current.

3.2. Conductive plates

Conductive plates of various sizes can be used to evaluate the performance of electrostatic charging systems, particularly in practical pesticide applications such as orchards, vineyards, and open-field spraying (Figure 3). For evaluation of the CMR, a plate, sized to fully intercept the spray angle at a set distance, is placed perpendicular to the spray trajectory to capture charged droplets. Upon impact, the droplets transfer their charge to the plate, generating an electric current measured by a connected sensitive ammeter. Aluminum plates have previously been employed to assess the CMR in the development of electrostatic charging systems with insulated electrodes for air blast sprayers (Amaya & Bayat, 2024a).

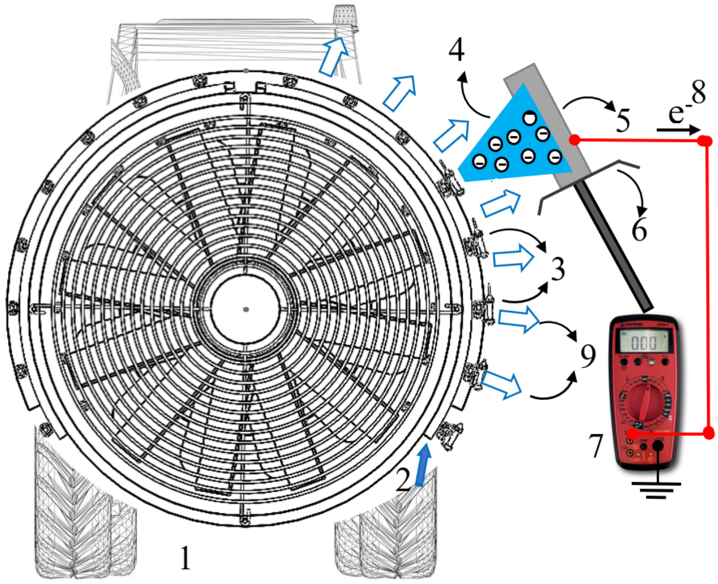

Figure 3. Measurement of electric current generated by charged droplets on the electrostatic sprayer using a conductive plate: 1–Air-assisted orchard sprayer; 2–Liquid inlet; 3–Electrostatic nozzles; 4–Charged droplets; 5–Conductive plate; 6–Insulating shield to prevent droplet contact with the operator; 7–Sensitive ammeter; 8–Electric current direction; airflow currents.

4. ASSESSMENT AND COMPARISON OF FARADAY CAGES AND CONDUCTIVE PLATES (Q2)

4.1. Air-assisted electrostatic nozzles

Law & Cooper (1987, 2024) and Wang *et al.* (2021) designed Faraday cages incorporating multiple aluminum meshes (2) enclosed within an outer shell (Figure 4). In Law and Cooper's setup, the cage is angled to allow spray liquid to drain through a rear hole, while in Wang *et al.*'s design, a collection vessel is positioned beneath the cage to capture the liquid. Both designs are effective, particularly when the tested nozzles (1) are located near the tunnel inlet, minimizing droplet and charge loss (1 mark). Unlike Law and Cooper's design, which lacks an outer protective layer (0 mark), Wang *et al.*'s device includes an insulating frame to reduce external discharge effects (1 mark). However, neither study provides detailed information about the microammeter (3) models used to measure the electric current (0 mark).

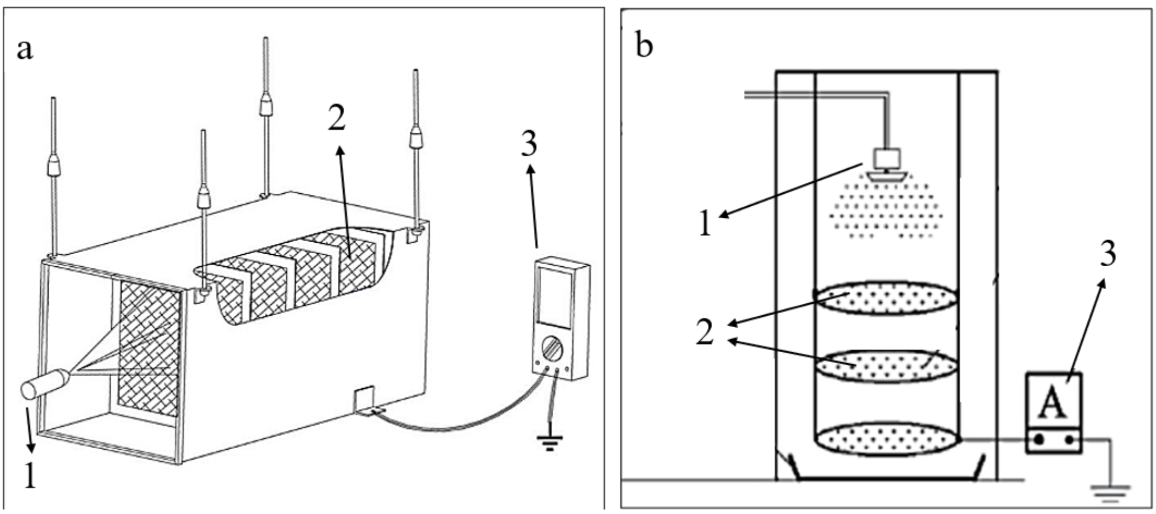

Figure 4. Faraday cages used by a: Law & Cooper (1987, 2024) and b: Wang *et al.* (2021).

Similar to previous designs, Mamidi *et al.* (2013) and Zhang *et al.* (2025) employed Faraday cages consisting of multiple mesh conductive layers to measure the electrical current induced by charged droplets. The electrostatic nozzle was positioned at the top, directing droplets into the cage, where a sensitive ammeter recorded the induced current (Figure 5). The multi-layer mesh systems employed in both studies effectively assess the CMR. However, the absence of protective housing around these layers may allow conductive liquid to leak through insulation points with ground, potentially causing the detected current to bypass the ammeter (0.5 mark). Additionally, the absence of an insulation layer leaves the design vulnerable to external discharge effects (0 mark). The measuring devices used, such as the Keithley 6514 and Keithley 6500, provide high accuracy (error <0.001 µA at typical readings of 0.5 µA) and high sensitivity with picoampere resolution (1 mark). The Faraday cage used by Mamidi *et al.* (2013) was subsequently adopted in several other studies (Patel *et al.*, 2013, 2015, 2016a, 2017).

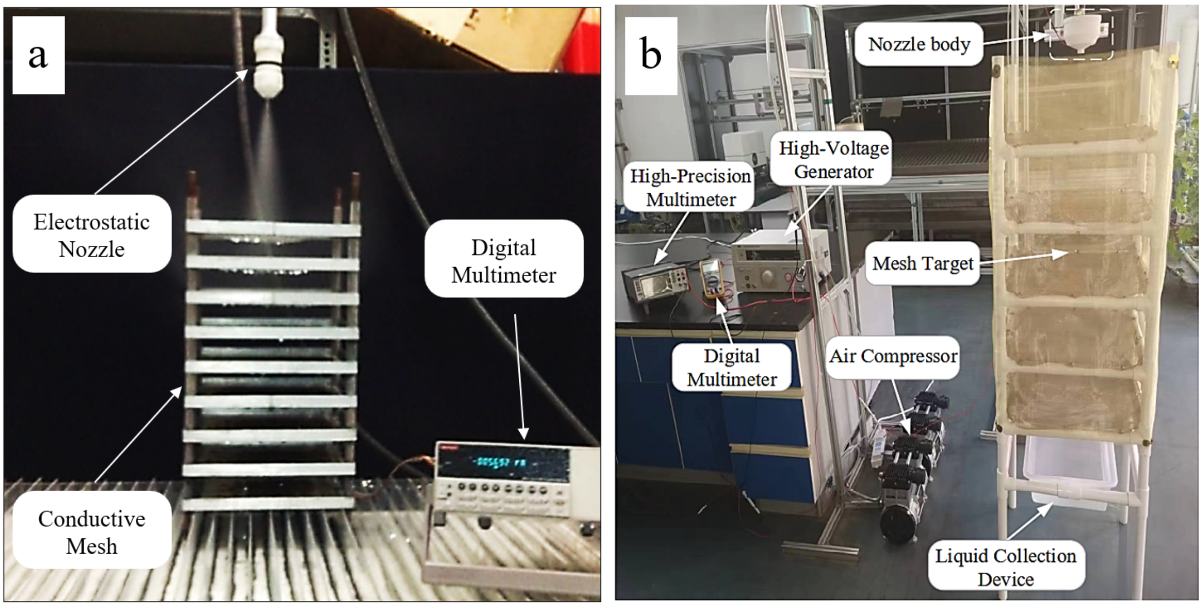

Figure 5. Faraday cages used by a: Mamidi *et al.* (2013) and b: Zhang *et al.* (2025).

Dai *et al.* (2022) and Zhou *et al.* (2024) introduced large cylindrical Faraday cages incorporating an insulating gasket to separate conductive and non-conductive components (Figure 6). The studies did not provide clear information about the conductive mesh, and most of the measured electric current likely resulted solely from the metallic cylinder capturing charged droplets. Additionally, at far nozzle positions, the horizontal spray direction may cause charge loss, as some droplets may fall before reaching the collection mesh, leading to measurement errors in the CMR (0.5 mark). Furthermore, these systems lacked an insulating layer to protect against external discharge influences (0 mark). The measuring devices used, such as the Fluke 8808A and Keithley 6485, provide high accuracy (error <0.001 µA at typical readings of 0.5 µA) and high sensitivity with picoampere resolution (1 mark).

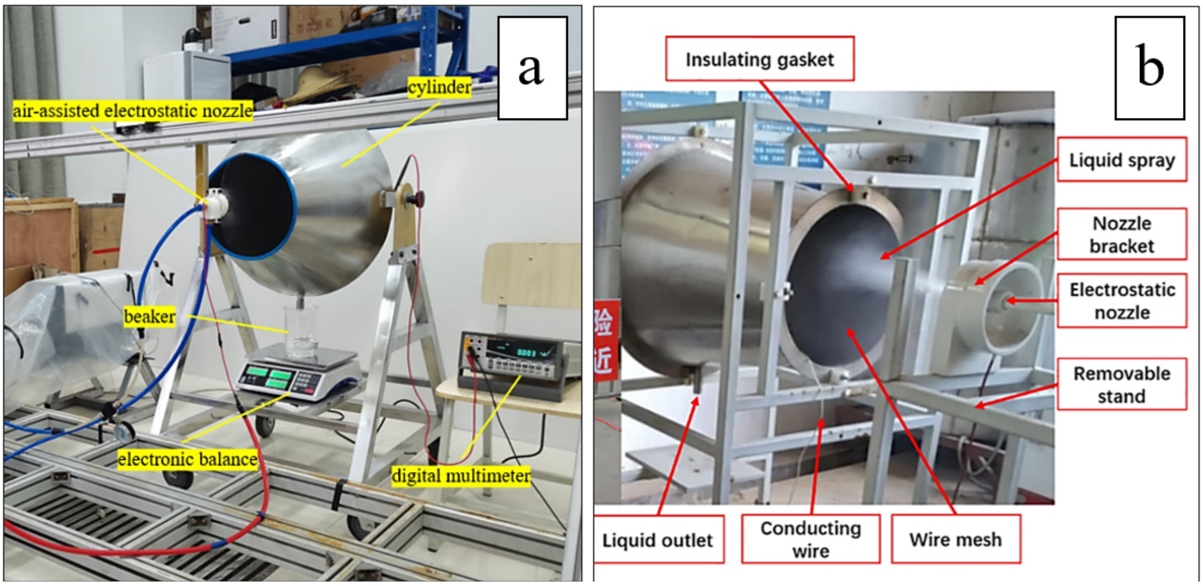

Figure 6. Faraday cages used in the studies by a: Dai *et al.* (2022) and b: Zhou *et al.* (2024).

Patel *et al.* (2013) used a rectangular aluminum plate (approximately 800 mm × 550 mm) instead of a Faraday cage to evaluate the CMR. In contrast, Zillgitt and Schmidt (2021) employed an aluminum wire mesh to capture electric charges from horizontally moving droplets, with a pan below to collect the liquid (Figure 7). The high conductivity of the aluminum plate makes it effective for assessing the CMR of the tested nozzle. However, droplets moving horizontally may fall due to gravity before reaching the plate surface, causing some measurement errors (0.5 mark). Additionally, in Zillgitt and Schmidt's setup, some charge may be lost during droplet travel, and the 4 mm mesh size may allow droplets to pass through without being captured, further affecting measurement accuracy (0 mark). The spray current reading on Patel et al.'s plate can be influenced by external discharge effects (0 mark). Although a container was used to reduce these effects in Zillgitt and Schmidt's mesh, it may be ineffective. Insulating the mesh itself is preferable, as environmental factors within the container can still affect measurements (0.5 mark). The measuring devices used in these studies, such as the Keithley 6514 and Keithley 6517B, offer high accuracy (error <0.001 µA at typical readings of 0.5 µA) and high sensitivity with picoampere resolution (1 mark). The aluminum plate was also reused in another study by Patel *et al.* (2016b), though the plate dimensions were not specified.

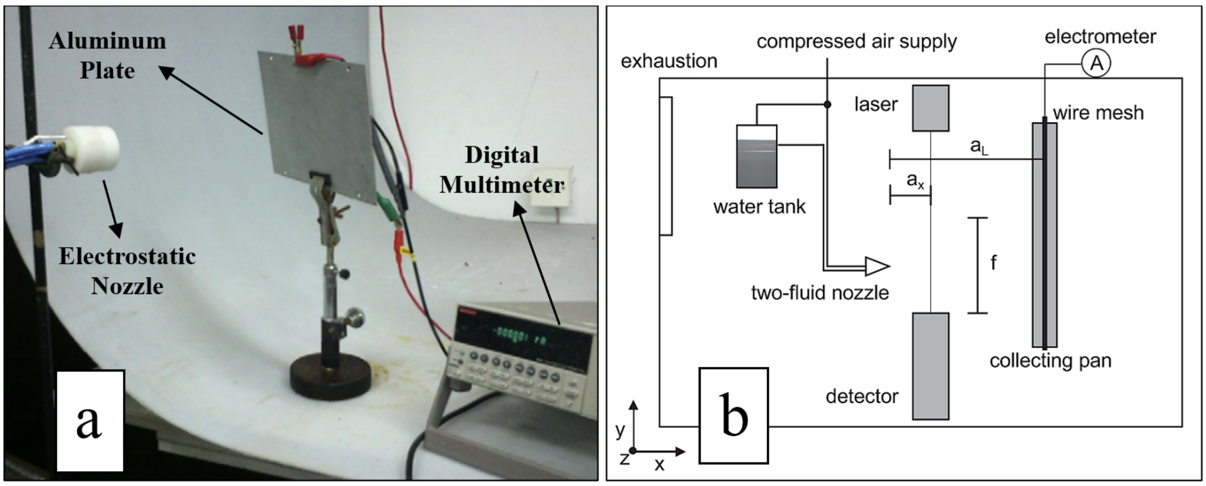

Figure 7. Aluminum plate and Conductive mesh used instead of a Faraday cage in the studies by a: Patel *et al.* (2013) and b: Zillgitt & Schmidt (2021).

Table 2. Technical specifications of the equipment used for evaluating the CMR of air-assisted electrostatic nozzles across various studies

References	Spraying pressure Liquid flow	Distance of the mesh layer from the nozzle Spraying angle	Design Geometry of Faraday cage (mark)	Isolation of Surrounding Environmental (mark)	Ampere meter (mark)	Charge-to-mass ratio	Score
(Law and Cooper, 2024, 1987)	207 kPa 0.073 l/min	0 *	Cubic with a capturing area of 305 mm × 305 mm and a length of 710 mm with five layers of Aluminum mesh (1)	No (0)	* (0)	4.1 mC/kg	1
(Mamidi *et al.*, 2013), (Patel *et al.*, 2017, 2016a, 2015)	240/*/350/400 kPa 0.365/0.25/0.13/0.15 l/min	0.3 m *	Cubic with a capturing area of 300 mm × 300 mm and a length of 600 mm with eight layers of Aluminum mesh (0.5)	No (0)	Keithley 6514 (1)	0.419/10.2/2.8/ 10 mC/kg	1.5
(Patel *et al.*, 2013)	1000 kPa 0.09 l/min	0.3 m *	813 mm × 560 mm aluminum plate positioned vertically on the horizontal droplet path without mesh (0.5)	No (0)	Keithley 6514 (1)	1.65 mC/kg	1.5
(Patel *et al.*, 2016b)	300 kPa 0.15 l/min	3-5 m *	Only an aluminum plate positioned vertically on the horizontal droplet path, without mentioning dimensions (0.5)	No (0)	Keithley 6514 (1)	~ 2.7 mC /kg	1.5
(Zillgitt and Schmidt, 2021)	700 kPa 0.097 l/min	0.88 *	Only a conductive wire mesh positioned vertically on the horizontal droplet path without mentioning dimensions (0)	Yes (0.5)	Keithley 6517b (1)	3 mC /kg	1.5
(Wang *et al.*, 2021)	* 0.18 l/min	0.5 m *	3 Conductive mesh inside insulating frame (1)	Yes (1)	* (0)	1.84 mC /kg	2
(Dai *et al.*, 2022)	60 kPa 0.45 l/min	* *	Horizontal bulky cylinder without conductive wire mesh (0.5)	No (0)	Fluke 8808A (1)	3 mC/kg	1.5
(Zhou *et al.*, 2024)	1500 kPa 0.2 l/min	0.1-1 m *	Bulky cylinder with conductive mesh inside (0.5)	No (0)	Keithley 6485 (1)	1.97 mC/kg	1.5
(Zhang *et al.*, 2025)	* 0.023 l/min	* 49.25°	Several layers of aluminum mesh (0.5)	No (0)	Keithley 6500 (1)	4.90 mC/kg	1.5

* Not mentioned.

Table 2 summarizes previous studies on the evaluation equipment used for measuring the CMR in agricultural electrostatic spraying, with a focus on the effects of Faraday cage or plate geometric designs, environmental isolation, and ammeter accuracy.

The distance between the nozzle and the mesh, as well as the spray angle, can affect measurement accuracy, particularly at high liquid and air flow rates. Therefore, these factors are included in the table. In contrast, droplet size and liquid properties do not directly influence the evaluation of the measurement equipment and are thus not included. Furthermore, cost information for each design was not presented in the tables, as such data were not provided in the cited studies.

Designs ranged from multi-layer aluminum mesh cages to simpler conductive plates, with most studies lacking complete environmental insulation, which may reduce measurement reliability. Ammeter precision varied across studies, with high-accuracy Keithley instruments being commonly employed. Reported CMR values spanned 0.42–10 mC/kg, reflecting differences in nozzle type, flow rate, and cage configuration. Overall scores, based on cage design, insulation, and ammeter accuracy, indicate Wang *et al.* (2021) as the most robust setup (score 2), while other studies scored 1–1.5. This highlights the importance of cage design, environmental isolation, and precise current measurement for reliable CMR evaluation.

4.2. Hydraulic Nozzles

Gan-Mor *et al.* (2014) employed a horizontally positioned wire mesh mounted on an insulating layer to capture and measure the electric charge of sprayed droplets (Figure 8). The simplistic insulation method may allow electrical current to bypass the microammeter, resulting in inaccurate readings. Additionally, the absence of a liquid drainage mechanism requires manual emptying after each experiment, exacerbating electrical leakage issues (0 marks). With an air velocity exceeding 10 m s^{-1}, intended to prevent electrode wetting, droplet trajectory deviations may occur, leading to inconsistent charge measurements (0 marks). The relatively small metal surface exposed to external discharge influences helps reduce potential charge dissipation (0.5 marks). The study used a UT 58A ammeter, capable of measuring electric currents down to the microampere range. At its 20 µA range, the device has an accuracy of ±(0.8% of the reading + 1 digit) with 0.01 µA resolution. For a reading of 0.5 µA, the actual value is expected to be 0.5 µA ± 0.014 µA (error ≤ 5%) (1 mark).

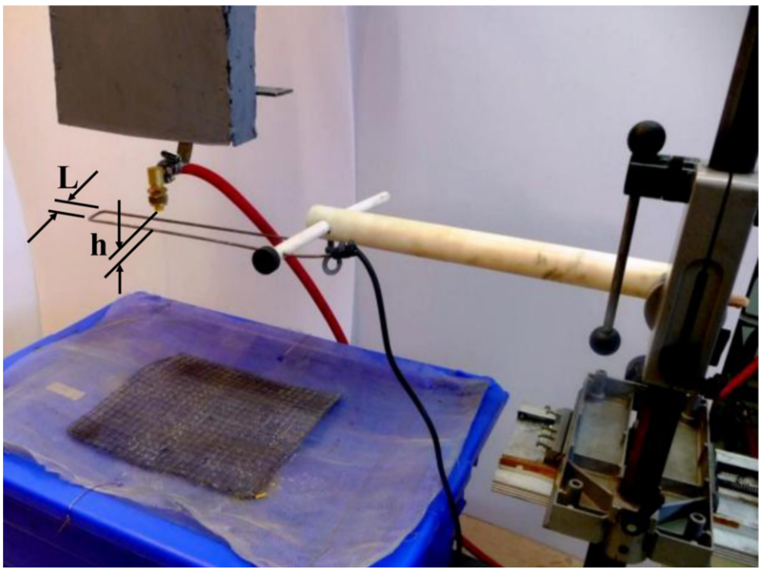

Figure 8. Faraday cage arrangement used by Gan-Mor *et al.* (2014).

Both Laryea & No (2003) and Krupa *et al.* (2013) employed Faraday cages constructed with multiple conductive mesh layers to ensure effective collection of the electric current generated by charged droplets (Figure 9). The meshes were enclosed within a dielectric layer to shield the collected charge from external interference (1 mark). However, both designs lacked a conductive inner housing connected to the mesh to discharge droplets accumulating on the dielectric layer before reaching the mesh (0.5 marks). Additionally, neither design incorporated an airflow disposal mechanism, which is critical for accurate measurements in experiments using hydraulic nozzles with external airflow (0 marks). Laryea's design included a sensitive ammeter (Keithley 6514) capable of measuring spray current with high accuracy (error ≤ 5%) (1 mark), whereas Krupa *et al.* (2013) did not provide details regarding the microammeter used (0 marks).

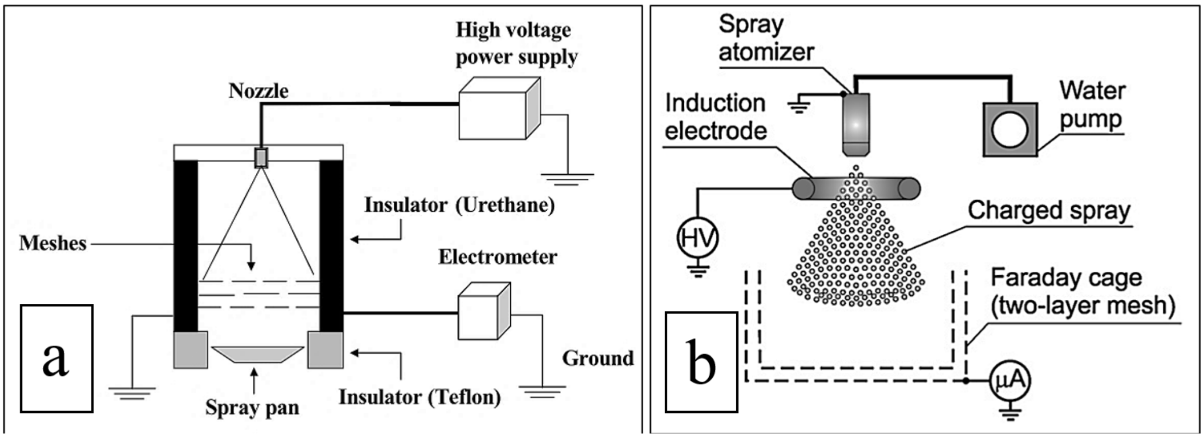

Figure 9. Faraday cages developed by a: Laryea & No (2003) and b: Krupa *et al.* (2013).

Li *et al.* (2022) and Herkins *et al.* (2025) also employed multiple conductive mesh layers positioned directly beneath the electrostatic spray nozzle to capture charged droplets (Figure 10). In both designs, the mesh assemblies were enclosed within a conductive barrel to discharge any droplets that did not reach the mesh layers (1 mark). This configuration was suitable for the study conditions, which involved relatively low operating pressures and flow rates. However, these barrels, functioning as Faraday cages, were not designed to allow airflow drainage. Consequently, mesh screens could cause droplets to rebound and wet nearby electrodes, potentially leading to electrical leakage and reduced measurement accuracy (0 marks). Li *et al.* (2022)'s design lacked an insulating layer to protect against external discharge influences (0 marks), whereas Herkins *et al.* (2025) electrically isolated the assembly inside a larger grounded 304L stainless steel vat using a PVC spacer (1 mark). Both designs incorporated a highly sensitive ammeter (Keithley 6514) capable of detecting electric currents with high accuracy in the picoampere range (1 mark).

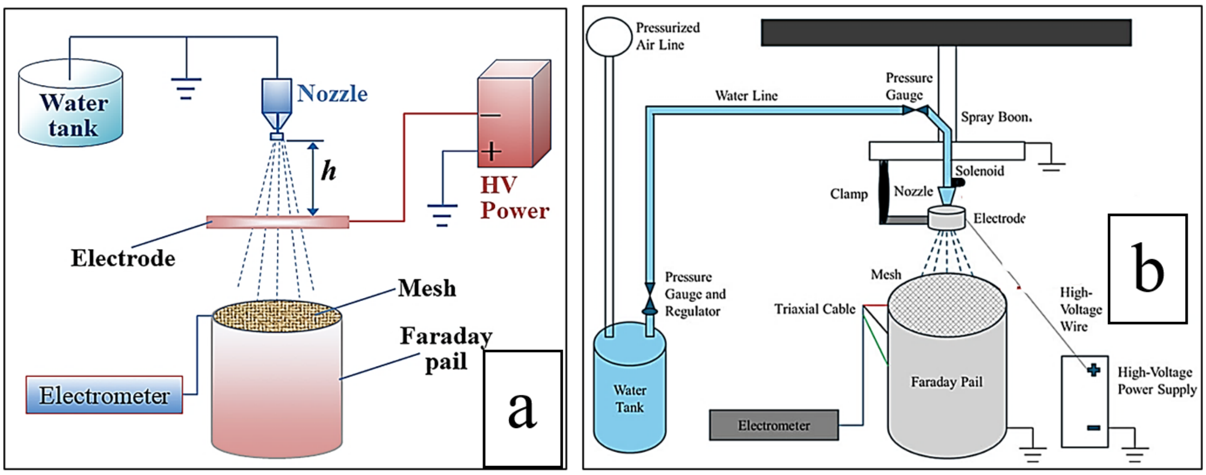

Figure 10. Barrels used as a Faraday cage by a: Li *et al.* (2022) and b: Herkins *et al.* (2025).

Martin & Carlton (2012, 2013) and Xue *et al.* (2023) used large containers to capture the electric charges emitted from electrostatic nozzles (Figure 11). However, it was unclear whether the devices incorporated wire mesh layers, and the horizontal trajectories of charged droplets could lead to partial losses before reaching the container inlet, potentially compromising measurement accuracy (0.5 marks). Additionally, these systems lacked an insulating layer to protect the container from external discharge influences, which could reduce measurement reliability (0 marks). Both studies incorporated airflow during the experiments, with Martin and Carlton's reaching velocities up to 96.11 m s^{-1}; however, neither reported any method for managing or draining the airflow (0 marks). Furthermore, details regarding the ammeter models used to measure spray electric current were not provided (0.5 marks).

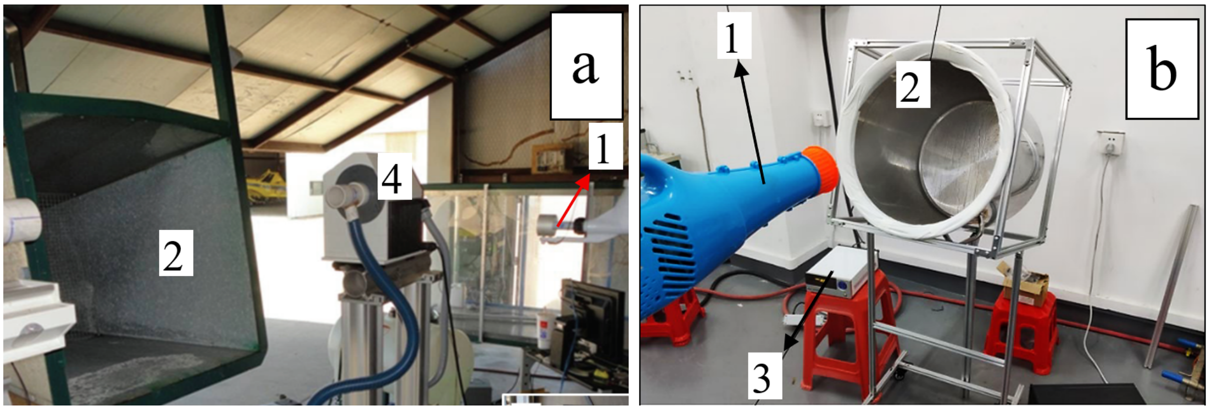

Figure 11. Containers used as a Faraday cage by a: Martin & Carlton (2012, 2013) and b: Xue *et al.* (2023).

Amaya &Bayat (2023) developed a Faraday cage consisting of a 1300 mm × 1300 mm dual aluminum mesh assembly positioned above and connected to a tray made from the same material (Figure 12). The large collection area effectively captures all sprayed droplets, minimizing charge loss and preventing droplet escape. The cage is electrically insulated from the ground using four insulating feet (1 mark). The wide aluminum mesh layers help dissipate the high kinetic energy of spray droplets, particularly under high airflow conditions, reducing droplet rebound and mitigating electrode wetting. Its open structural design also facilitates smooth lateral airflow discharge, preventing turbulence that could distort CMR measurements. The effectiveness of this configuration was validated through comparative analysis with alternative designs incorporating additional mesh layers and varying geometries (Amaya & Bayat, 2024b), confirming that the system maintains accuracy at air velocities up to 30 m s^{-1} without introducing measurement errors (1 mark). However, the absence of an external insulating layer increases susceptibility to external discharge influences (0 marks). The study used a 30XR-A ammeter, which provides microampere-range measurements; however, at its 200 µA range, the device has an accuracy of ± (1.5% of the reading + 1 digit) with 0.1 µA resolution. For a 0.5 µA reading, the actual value could be 0.5 µA ± 0.11 µA (error > 10%) (0 marks).

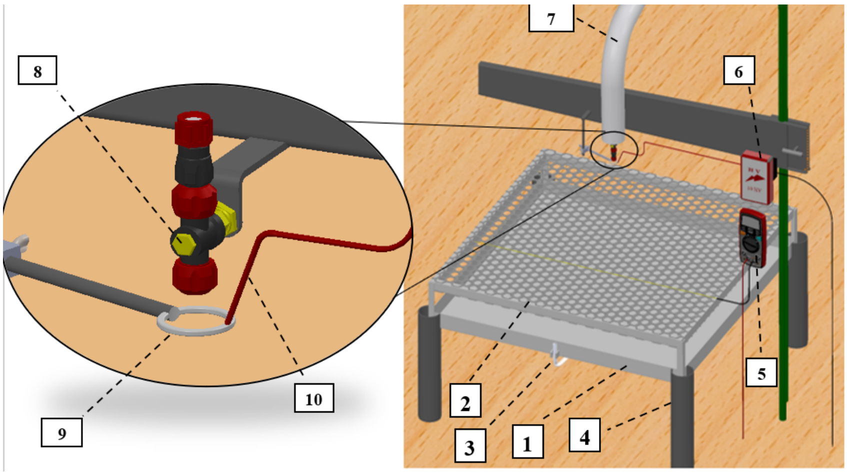

Figure 12. Schematic of the Faraday cage used by Amaya & Bayat (2023): 1–Aluminum tray; 2–Two layers of aluminum mesh; 3–Plastic hose for draining water after each experiment; 4–Four plastic feet to electrically insulate the tray from the ground; 5–Ammeter; 6–High-voltage source (Amaya, 2024); 7–Air-assisted blower duct; 8–Hydraulic nozzle; 9–Charging electrode; 10–High-voltage cable.

Li *et al.* (2025) presented a Faraday cage design incorporating a copper mesh assembly with openings of 80, 200, and 400 mesh, arranged from the inside outward (Figure 13). The multiple mesh layers enable efficient capture of all electrical charges, while the surrounding metal casing prevents leakage paths to ground (1 mark). The mesh arrangement, with the largest openings on the inside and the smallest on the outside, dissipates the kinetic energy of droplets under high flow conditions and minimizes air vortex formation, reducing droplet rebound and mitigating electrode wetting (1 mark). However, the device lacks an insulating layer to protect against external discharge influences (0 marks). The ammeter used (Keithley 6487) provides high-accuracy spray current measurements, with an error percentage ≤ 5% (1 mark).

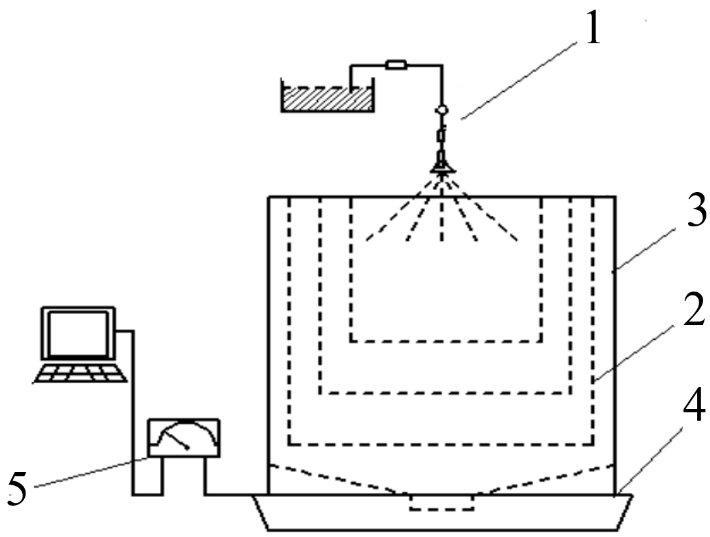

Figure 13. Faraday cage used by Li *et al.* (2025): 1- Spraying and charging unit, 2- Conductive mesh layers, 3- Outer shell, 4- Drainage channel, and 5- Spray current measuring unit.

Table 3 summarizes key features of previous studies assessing the CMR in agricultural electrostatic spraying. Scores were calculated out of four based on Faraday cage design (geometry and mesh configuration), environmental isolation, ammeter accuracy, and the method of managing applied airflow. As in the previous table, droplet size and liquid properties do not directly affect the evaluation of the measurement equipment and are therefore not included.

Table 3. Technical specifications of the equipment used for evaluating the CMR of electrostatic hydraulic nozzles in various studies

References	Spraying pressure Liquid flow	Distance of the mesh layer from the nozzle Spraying angle	Design Geometry of Faraday cage (mark)	Isolation of Surrounding Environmental (mark) **	Suitable for air flow (mark)	Ampere meter Model (mark)	Charge-to-mass ratio	Score
(Laryea and No, 2003)	2500 kPa 0.79 l/min	0 *	Three Aluminum conductive meshes within an insulating container (1)	Yes (0.5)	* (0)	Keithley 617 (1)	0.27 mC/kg	2.5
(Martin and Carlton, 2013, 2012)	517 kPa 0.85 l/min	0.79 TX-VK12 (80°)	Pyramid-shaped Faraday cage with its base oriented toward the electrostatic nozzle (0.5)	No (0)	96 m/s (0)	Simpson (Analog) (0.5)	0.89 mC/kg	1
(Krupa *et al.*, 2013)	600 kPa 1.96 l/min	* Full cone *	Two layers of copper mesh inside an insulating cylinder (0.5)	Yes (1)	0.3 m/s (0)	* (0)	0.16 mC/kg	1.5
(Gan-Mor *et al.*, 2014)	400 kPa 0.45 l/min	0.24 m *	Only conductive mesh horizontally positioned on an insulated concave table (0)	No	>10 m/s (0).	UT 58A (0.5)	1.85 mC/kg	1.5
(Li *et al.*, 2022)	300 kPa 0.41 l/min	* TX-VK6 (80°)	Cylindrical barrel with conductive wire mesh (1)	No (0)	* (0)	Keithley 6514 (1)	0.435 mC/kg	2
(Xue *et al.*, 2023)	700 kPa 1.56 l/min	0 cone nozzle (65°)	Horizontal bulky cylinder with a 450 mm diameter and height 500 mm without conductive mesh (0.5)	No (0)	10 m/s (0)	HEST-112A (0.5)	Unclear	1
(Amaya and Bayat, 2023)	600 kPa 0.959 l/min	500 m *	1300 mm × 1300 mm aluminum tray with 80 mm depth, and with two aluminum mesh screens positioned above it by 60 mm (1)	No (0)	25 m/s (1)	Amprobe 30XR-A (0)	0.5 mC /kg	2
(Herkins *et al.*, 2025)	276 kPa 1150 l/min	0.2 m TX-VK18 (80°)	An aluminum mesh screen attached to the Faraday pail to collect charged droplets (1)	Yes (1)	* (0)	Keithley 6514 (1)	0.163 mC /kg	3
(Li *et al.*, 2025)	350 kPa 1280 l/min	0.2-1.0 flat fan (110°)	Copper mesh layers inside a metal casing prevent the leakage paths (1)	No (0)	* (1)	Keithley 6587 (1)	1.62 mC/kg	3

* Not mentioned.

Designs ranged from multi-layer aluminum or copper mesh cages to large containers and trays, with some systems lacking mesh entirely. Most studies did not provide full environmental insulation, potentially compromising measurement reliability, and only a few designs were suitable for handling high airflow conditions. Ammeter precision varied, with high-accuracy Keithley models commonly used, while some studies employed less-sensitive or analog meters.

Reported CMR values ranged from 0.16 mC/kg to 1.85 mC/kg, reflecting differences in nozzle type, flow rate, cage configuration, and airflow conditions. Overall scores indicate that the designs by Herkins *et al.* (2025) and Li *et al.* (2025) achieved the highest robustness (score 3), while other setups scored between 1 and 2. These findings emphasize the critical role of cage design, environmental shielding, airflow management, and precise current measurement in ensuring reliable CMR evaluation in agricultural electrostatic spraying systems.

5. KEY SPECIFICATIONS FOR DESIGNING CMR EVALUATION EQUIPMENT (Q3)

Designing charge-to-mass ratio evaluation equipment requires careful consideration of key engineering specifications to ensure accurate and reliable measurements.

5.1. Faraday cage

5.1.1. Selection of material for Faraday cage construction

The Faraday cage functions by capturing electrical charges from spray droplets and transferring them as electric currents measurable by a sensitive ammeter. Therefore, the cage must be constructed from a material with high electric conductivity to accurately measure the small electric current generated by minimal charges, particularly when dealing with fine droplets or aerosols. Higher conductivity ensures efficient transfer of electric charge from the charged droplets to the ammeter, which is critical for precise and reliable measurements.

However, the materials selected for the cage must exhibit durability, especially in environments where they are exposed to liquids or chemicals. The cage should possess corrosion resistance to maintain both its electrical conductivity and structural integrity over time. Additionally, the cage material should facilitate ease of cleaning and maintenance without compromising its electrical properties.

Copper with a conductivity of approximately 5.96×10^7 S/m offers one of the highest electrical conductivities, making it ideal for sensitive charge detection. However, despite its superior conductivity, copper is relatively expensive and susceptible to corrosion when exposed to water or humidity. This corrosion results in the formation of copper oxide on its surface, which can degrade conductivity and compromise measurement accuracy.

In contrast, aluminum, with a conductivity of around 3.77×10^7 S/m, on the other hand, is frequently preferred in practical applications due to its good conductivity, lightweight nature, low cost, and superior corrosion resistance. These properties render aluminum more durable than copper in moist or wet environments.

Stainless steel presents a cost-effective and environmentally resistant alternative suitable for long-term applications involving exposure to water or humidity. Nevertheless, its relatively low conductivity (~1.25×10^6 S/m) compared to copper and aluminum limits its suitability for manufacturing Faraday cages in precision research applications.

5.1.2. Faraday cage size and geometry design

Generally, Faraday cages should comprise a conductive mesh for capturing electrical charges from spray droplets and a connected conductive container for collecting the sprayed liquid. The container plays a critical role in collecting droplets and preventing electrical leakage that may occur through the conductive liquid path between the charged mesh and ground. To ensure complete discharge of accumulated charge, the container should be fabricated from the same conductive material as the mesh and electrically connected to the same microammeter.

The size and geometric design of the Faraday cage must be compatible with the operating parameters and spray angle to guarantee accurate charge measurements. For experiments involving low spraying pressure and liquid flow rates, the cage should be relatively small to minimize external influences on the charging process. Conversely, for experiments with high flow rates and pressures, the cage must be sufficiently large to fully enclose the droplet passage region.

When airflow is employed to mitigate electrode wetting, the design must include an air drainage outlet that allows the airflow passage without generating strong air disturbances around the capturing meshes, which could otherwise alter the droplet trajectories and cause droplet rebound (Figure 14). Large Faraday cages, while accommodating such requirements, may introduce undesirable variables, such as external discharge effects, and incur higher costs and spatial demands.

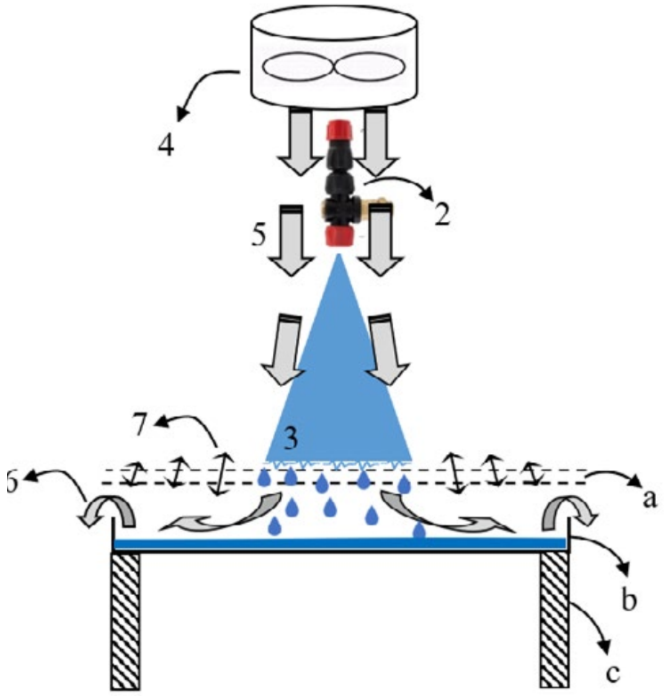

Figure 14. Airflow currents inside the Faraday cages designed by Amaya & Bayat (2023): 1–Faraday cage (a–Aluminum wire mesh, b–Aluminum tray, c–Electrical insulation), 2–Spraying nozzle, 3–Spray cone, 4–Air blower, 5–Airflow currents, 6–Air exiting the cage, 7–Movement of aluminum wire meshes under droplet and airflow impact.

To improve the accuracy of the measurement, the design of the Faraday cage should be selected according to the nozzle spray pattern. Cylindrical Faraday cages are commonly used with conical electrostatic nozzles, as they facilitate even charge distribution across the inner surface. Alternatively, box-shaped cages can be adapted to specific spray systems, offering design flexibility for varied experimental setups. The design must balance sufficient space for droplet movement and precise control of the measurement environment.

Finally, it is essential to empty the collected liquid after each charging trial to prevent electrical leakage through the liquid, which could interfere with subsequent measurements and compromise system accuracy.

5.1.3. Isolation from the ground

The Faraday cage must be mounted on insulating supports to ensure that it retains its charge and that the collected charge originates exclusively from the droplets. When charged droplets contact the conductive mesh without adequate electrical isolation from the ground, current leakage can occur. Such leakage compromises the cage's ability to stay electrically isolated, thereby impairing its primary function of accurately measuring only the charge induced by the passing droplets.

The material used to isolate the Faraday cage from the ground should possess high dielectric strength and excellent insulation properties. Furthermore, the insulating supports must be strategically positioned to avoid contact with the spray liquid, preventing the formation of a conductive film that could establish an unintended connection between the cage and ground, resulting in electrical leakage.

5.1.4. Insulation of external discharge influences

Faraday cages can be designed with three layers: an inner and outer conductive layer separated by a middle insulating layer. The inner conductive layer serves as a housing for the conductive mesh and as a collector for any electric charges from spray droplets not capturing directly by the conductive mesh. In contrast, the outer conductive layer should be grounded to eliminate the external discharge influences that could compromise measurement accuracy.

Without proper insulation of the inner conductive layer, ambient electrical fields or nearby equipment may cause the induction of additional charges on the cage, resulting in false readings or electrical noise in the data. Grounding the outer layer ensures that unwanted charges are safely discharged, keeping the system electrically neutral except for charges induced by droplets. The grounding provides a stable reference potential and guarantees that the measured charge originates solely from the droplets, a critical factor in environments with high electrical activity or sensitive measurement setups near other operating equipment.

5.1.5. Electrometer connection and sensitivity

The Faraday cage should include a connection point for a highly sensitive ammeter. Selecting a high-accuracy device minimizes measurement error and ensures a reliable assessment of charging efficiency. For example, Device 1 (UT60EU), operating in a 1 mA range with ± (0.8% + 3) accuracy, produces a total error of ~3.04 µA when measuring 5 µA. This yields a current range of 1.96 to 8.04 µA, making the reading unreliable. In contrast, Device 2 (UT89X), set to a 60 µA range with ±(0.8% + 8) accuracy, has a total error of only 0.12 µA, giving a much tighter range of 4.88 to 5.12 µA. Consequently, the UT60EU shows approximately ±60% error at 5 µA, whereas the UT89X shows only ~2.4%. Selecting a high-accuracy microammeter minimizes measurement error and ensures reliable assessment of charging efficiency.

5.2. Conductive plates

Conductive plates can be fabricated and used as alternative to Faraday cages for evaluating the CMR of spray droplets. When designing and using these plates, several engineering considerations must be considered to ensure measurement accuracy and safe operation, including:

5.2.1. The geometric design and distance from the nozzle

The size and position of conductive plates must correspond to the spray pattern generated by each type of nozzle and be sufficient to capture all charged droplets. Electrostatic nozzles with a wide spray angle need bigger conductive plates than nozzles with a narrow spray angle, when measured at the same distance. As shown in Figure 15-a, these big plates provide high-accuracy measurements as they maximize the collection of the charged droplets. However, under high-velocity airflow conditions, handling large plates can be physically demanding due to the greater force required to counteract the air currents. For rapid assessments, particularly when verifying the performance of an electrostatic nozzle under practical pesticide application conditions, smaller plates offer greater convenience (Figure 15-b).

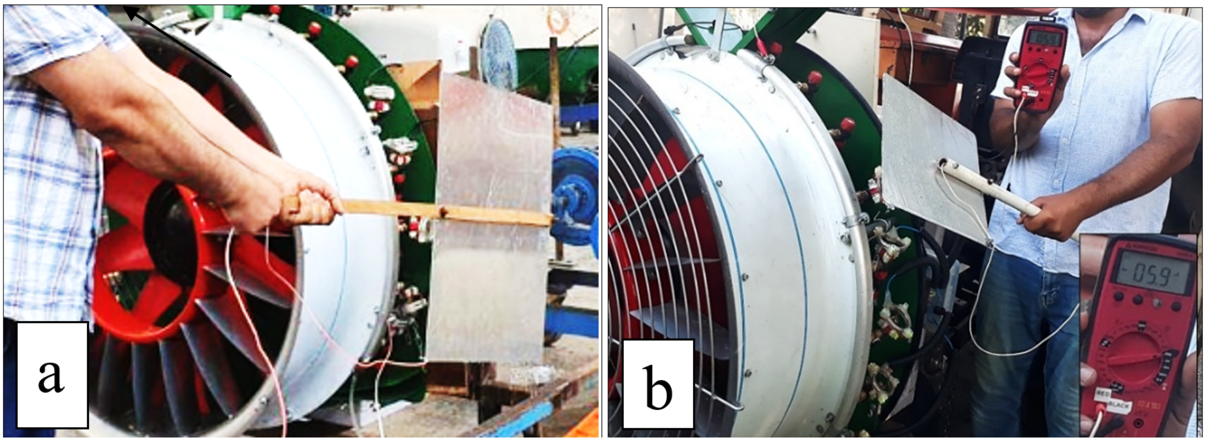

Figure 15. Use of large (a) and small (b) aluminum plates for evaluating the CMR.

The plate should be positioned as close as possible to the nozzle outlet to minimize charge dissipation and avoid altered droplet trajectories, which could lead to inaccurate readings. Conversely, placing the plate too close may cause droplets to rebound onto the electrode, exacerbating electrode wetting, reducing the charging efficiency. Proper selection of plate distance, considering spray pattern and plate size, ensures uniform droplet impact and enhances measurement reliability.

To ensure accurate readings on the ammeter, plate handles must be made from insulating material and equipped with a dielectric shield to prevent droplet from contacting the operator, as such contact can alter the measured current and compromise result accuracy.

5.2.2. Measuring the electric current for each electrostatic nozzle separately

Measuring the electric current from each electrostatic nozzle individually eliminates potential interference between the spray cones of multiple nozzles, which could otherwise result in inaccurate readings. By isolating measurement to a single nozzle, the actual CMR and the individual performance characteristics of that nozzle can be determined accurately, ensuring more reliable and consistent results in electrostatic spraying applications.

5.2.3. Avoiding the use of conductive plates in the laboratory evaluations

Conductive plates are recommended for assessing the charging efficiency of electrostatic spraying systems primarily under field or practical application conditions, where the nozzles are mounted on sprayers. Some studies, however, have used these plates for laboratory-based evaluations of the CMR instead of a Faraday cage (Patel *et al.*, 2013, 2016b). This approach can yield inaccurate, as it may fail to capture all charged droplets or allow electrical leakage. When droplets contact the metal plate, a conductive liquid film can form between the plate and the ground, creating a leakage path and introducing errors in the CMR measurements. In contrast, a Faraday cage fully encloses the droplet stream, isolating them from potential leakage paths and external fields, thereby ensuring more reliable and accurate charge-to-mass measurements.

5.3. Future Directions in Electrostatic Spraying Technology and Charge Measurement

Future trends in electrostatic spraying technology and charge measurement are expected to focus on several key advancements. While the idea of a single, universally accepted CMR meter is appealing, a more practical approach is to establish standardized operating conditions for CMR assessment, analogous to the ISO 25358 standard for spray droplet size measurement. Such a framework would not require a specific device but would define a set of reference operating parameters such as nozzle types, operating pressures, standard test liquids, and environmental conditions.

Such standardization would allow researchers and manufacturers to consistently evaluate and compare CMR measurements across different instruments, fostering reliability and building a robust comparative dataset across the field without requiring a single standardized device. International guidelines for assessing electrostatic spraying efficiency will be pivotal in promoting standardized practices and ensuring accurate, reproducible, and comparable results.

Advances in Faraday cage design will also be critical, with improved materials and optimized geometries enhancing measurement accuracy while reducing external interference. The development of miniaturized and portable Faraday cages for field-based CMR evaluations will broaden the applicability of electrostatic spraying systems, facilitating adoption in diverse agricultural settings.

Additionally, advanced sensors capable of continuously measuring CMR in real time during field applications will enable operators to monitor spray charging, make immediate adjustments, and improve spray efficiency under varying environmental conditions.

6. CONCLUSIONS

This study emphasizes the critical role of accurate CMR measurement in the development of electrostatic spraying systems. Analysis of Faraday cages and conductive plates demonstrates that design, material choice, insulation, and measurement sensitivity greatly influence the reliability of charge assessments. The findings highlight the need for standardized methodologies to ensure consistency comparability across studies. Optimizing CMR measurement techniques can enhance the efficiency of electrostatic spraying systems, resulting in better pesticide deposition, reduced chemical waste, and enhanced environmental sustainability. Future research should focus on refining measurement methods and advanced sensor technologies capable of continuously monitoring CMR during field applications.

Supplementary information ↑

Funding sources

Scientific and Technological Research Council of Türkiye 223O176

Supplementary material

Not applicable.

Data availability

Not applicable.

Acknowledgements

I would like to express my sincere gratitude to Dr. Ramon Salcedo from Polytechnic University of Catalonia, Barcelona, Spain for his valuable help in improving the paper. His support greatly enhanced the quality and clarity of the work.

Authorship contribution statement

Kemal Amaya: Writing – original draft, Writing – review & editing, Investigation, Methodology, Validation, Data curation, Formal analysis.

Ali Bayat: Investigation, Methodology, Supervision, Writing – review & editing.

Competing interests

The authors have declared that no competing interests exist.

Statement on the use of Artificial Intelligence

The author(s) employed ChatGPT in order to improve paragraph structure, clarity, and readability while preparing this work. Following their use, the author(s) assumed full responsibility for the publication's content and reviewed and edited it as necessary.

Declaration: This study does not aim to negatively criticize previous works but rather provides a critical analysis reflecting the authors' perspective to improve the design of the Faraday cage.

REFERENCES

Almourrh A, Alsalmo A, Mousa S, AlTaweel K, 2024. Effect of some fungicides on Fusarium oxysporum f. sp. lycoprsici Colony growth in the laboratory. African J Biol Sci 6(13): 1979–1995. https://doi.org/10.48047/AFJBS.6.13.2024. 1979-1995

Almourrh A, Wahab J A, Alsalmo A, Hamijo T, Nawaz H, Kayim M, Arpacı B B, 2025. Comparative Study of Biological and Chemical Control for Fusarium Wilt in Tomato. Diyala Agric Sci J 17: 209–221. https://doi.org/10.52951/dasj.25170116

Alsalmo A, Hamijo T, Kayim M, Al-Mourrh A, 2025. Plant Disease Resistant in the Triticum. in: Triticum - The Pillar of Global Food Security. IntechOpen, pp. 1–33. https://doi.org/10.5772/intechopen.1009386

Amaya K, 2024. Low-cost high voltage generator for electrostatic charging of pesticide droplets, and laboratory uses. Gazi J Eng Sci 9: 422–434. https://doi.org/10.30855/gmbd.07050776

Amaya K, Bayat A, 2024a. Innovating an electrostatic charging unit with an insulated induction electrode for air-assisted orchard sprayers. Crop Prot. 181: 106701. https://doi.org/10.1016/j.cropro.2024.106701

Amaya K, Bayat A, 2024b. Optimizing Charging Efficiency: The Influence of Electrode Age and Faraday Cage Design on Electrostatic Spraying Systems for Pesticide Application. 4. Bilsel International Çatalhöyük Scientific Researches Congress, Türkiye (Konya), Nov 23-24. pp: 492–501.

Amaya K, Bayat A, 2023. Determining effects of induction electrode geometry on charging efficiency of droplets in pesticide electrostatic spraying applications. Smart Agric Technol 4, 1–7. https://doi.org/10.1016/j.atech.2023.100190

Blettler D.C, Biurrun Manresa J.A, Fagundez G.A, 2022. A review of the effects of agricultural intensification and the use of pesticides on honeybees and their products and possible palliatives. Spanish J Agric Res 2. https://doi.org/10.5424/sjar/2022204-19516

Cunha J P A R Da, Barizon R R M, Ferracini V L, Assalin M R, 2017. Spray drift and caterpillar and stink bug control from aerial applications with electrostatic charge and atomizer on soybean crop. Eng Agric 37: 1163–1170. https://doi.org/10.1590/1809-4430-Eng.Agric.v37n6p1163-1170/2017

Dai S, Zhang J, Jia W, Ou M, Zhou H, Dong X, Chen H, Wang M, Chen Y, Yang S, 2022. Experimental study on the droplet size and charge-to-Mass ratio of an air-assisted electrostatic nozzle. Agriculture 12: 889. https://doi.org/10.3390/agriculture12060889

Durairaj D, Jyoti B, 2023. A method to optimize the pesticide dose considering the combined influence of plant pest pesticide and spray equipment on bioefficacy. Spanish J Agric Res. 21: e0208. https://doi.org/10.5424/sjar/2023213-19738

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

Garcia L C, Carraro G H, Felema S, Fornari A J, Sformi L J V, Inagaki T M, 2024. Adjuvants used in fungicide spraying on soybean plants. Spanish J Agric Res 22: e1003. https://doi.org/10.5424/sjar/2024223-20497

Herkins M, Zhao L, Zhu H, Jeon H, Castilho-Theodoro J, 2025. Optimization and Evaluation of Electrostatic Spraying Systems and Their Effects on Pesticide Deposition and Coverage Inside Dense Canopy Plants. Agronomy 15: 1401. https://doi.org/10.3390/agronomy15061401

Hu H, Kaizu Y, Huang J, Furuhashi K, Zhang H, Xiao X, Li M, Imou K, 2022. Design and performance test of a novel UAV air-assisted electrostatic centrifugal spraying system. Int J Agric Biol Eng 15: 34–40. https://doi.org/10.25165/j.ijabe.20221505.6891

Kayim M, Endes A, Alsalmo A, Yasmin S, Nawaz H, 2022. Preliminary evaluation of citrus rootstocks and scions to four different bot canker pathogens. XIV International Citrus Congress, Türkiye (Mersin), Nov 6-11, p: 403–410.

Krupa A, Jaworek A, Sobczyk A.T, Marchewicz A, Szudyga M, Antes T, 2013. Charged spray generation for gas cleaning applications. J Electrostat 71: 260–264. https://doi.org/10.1016/j.elstat.2012.11.022

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

Law S E, Cooper S C, 2024. Standard Methods for Evaluating Electrostatic Spray Charge and Deposition of Conductive Liquids used for Surface Disinfection. IEEE Trans Ind Appl 60(6): 8371–8382. https://doi.org/10.1109/tia.2024.3457743

Law S E, Cooper S C, 1987. Induction Charging Characteristics of Conductivity Enhanced VegetableOil Sprays. Trans Am Soc Agric Eng 30: 75–79. https://doi.org/10.13031/2013.30405

Li X, Knight R M, Hocter J, Zhang B, Zhao L, Zhu H, 2022. Effects of electrode materials and dimensions of an electrostatic spray scrubber on water droplet charging for dust removal. J Air Waste Manag Assoc 72: 1442–1453. https://doi.org/10.1080/10962247.2022.2120564

Li Y, Li Q, Hu J, Liu C, Zhao S, Zhang W, Wang Y, 2025. An Experimental Study on the Charging Effects and Atomization Characteristics of a Two-Stage Induction-Type Electrostatic Spraying System for Aerial Plant Protection. Agronomy 15: 1641. https://doi.org/10.3390/agronomy15071641

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

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: 5–10. https://doi.org/10.13031/2013.42528

Martin D E, Carlton J B, 2012. Airspeed and orifice size affect spray droplet spectra from an aerial electrostatic nozzle for rotary-wing applications. At sprays 22: 997–1010. https://doi.org/10.1615/AtomizSpr.2013006280

Page M J, McKenzie J E, Bossuyt P M, Boutron I, Hoffmann T C, Mulrow C D, Shamseer L, Tetzlaff J M, Akl E A, Brennan S E, 2021a. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. bmj 372. https://doi.org/10.1136/bmj.n71

Page M J, Moher D, Bossuyt P M, Boutron I, Hoffmann T C, Mulrow C D, Shamseer L, Tetzlaff J M, Akl E A, Brennan S E, 2021b. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. bmj 372. https://doi.org/10.1136/bmj.n160

Patel M K, Ghanshyam C, Kapur P, 2013. Characterization of electrode material for electrostatic spray charging: Theoretical and engineering practices. J Electrostat 71: 55–60. https://doi.org/10.1016/j.elstat.2012.11.019

Patel M K, Kundu M, Sahoo H K, Nayak M K, 2016a. Enhanced performance of an air-assisted electrostatic nozzle: Role of electrode material and its dimensional considerations in spray charging. Eng Agric Environ Food 9: 332–338. https://doi.org/10.1016/j.eaef.2016.05.002

Patel M K, Praveen B, Sahoo H K, Patel B, Kumar A, Singh M, Nayak M K, 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, Ghanshyam C, 2016b. Plausibility of variable coverage high range spraying: Experimental studies of an externally air-assisted electrostatic nozzle. Comput. Electron Agric 127: 641–651. https://doi.org/10.1016/j.compag.2016.07.021

Patel M K, Sahoo H K, Nayak M K, Ghanshyam C, 2015. Electrostatic Nozzle: New Trends in Agricultural Pesticides Spraying. SSRG Int J Electr Electron Eng. April 13-15. PP: 6–11.

Salcedo R, Llop J, Campos J, Costas M, Gallart M, Ortega P, Gil E, 2020. Evaluation of leaf deposit quality between electrostatic and conventional multi-row sprayers in a trellised vineyard. Crop Prot 127: 104964. https://doi.org/10.1016/j.cropro.2019.104964

Salcedo R, Sánchez E, Zhu H, Fàbregas X, García-Ruiz F, Gil E, 2023. Evaluation of an electrostatic spray charge system implemented in three conventional orchard sprayers used on a commercial apple trees plantation. Crop Prot 167: 106212. https://doi.org/10.1016/j.cropro.2023.106212

Wang S, Li X, Zhou H, Lv X, Shen W, 2021. Design and experiment of an aerial electrostatic spraying system for unmanned agricultural aircraft systems. Appl Eng Agric 36: 955–962. https://doi.org/10.13031/AEA.14150

Xue X, Zeng K, Li N, Luo Q, Ji Y, Li Z, Lyu S, Song S, 2023. Parameters Optimization and Performance Evaluation Model of Air-Assisted Electrostatic Sprayer for Citrus Orchards. Agriculture 13: 1498. https://doi.org/10.3390/agriculture13081498

Zhang L, Li Z, Chu H, Chen Q, Li Y, Liu X, 2025. Design and Evaluation of a Novel Efficient Air-Assisted Hollow-Cone Electrostatic Nozzle. Agriculture 15: 1293. https://doi.org/10.3390/agriculture15121293

Zhao D, Cooper S, Chima P, Wang G, Zhang L, Sun B, Zhang X, Lan Y, 2024. Development and Characterization of a Contact-Charging Electrostatic Spray UAV System. Agriculture-Basel 14: 467. https://doi.org/10.3390/agriculture14030467

Zhou H, Ou M, Dong X, Zhou W, Dai S, Jia W, 2024. Spraying performance and deposition characteristics of an improved air-assisted nozzle with induction charging. Front Plant Sci 15: 1309088. https://doi.org/10.3389/fpls.2024.1309088

Zillgitt M, Schmidt E, 2021. Determination of operating parameters for the use of an electrostatically charged water spray mist. Chem Eng Technol 44: 1178–1184. https://doi.org/10.1002/ceat.202100003