

AIR-ASSISTED ELECTROSTATIC SPRAYS FOR POSTHARVEST CONTROL OF FRUIT AND VEGETABLE SPOILAGE MICROORGANISMS

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Abstract - Losses of foodstuffs following harvest can often exceed 10-30%, much due to various fungal and other microorganisms which degrade the food in shipment and storage. In addition to these direct losses due to spoilage, certain microorganisms render foods unsafe for human consumption by natural toxins which they produce. To maintain quality and desired sensory attributes between farm and market, other fruits and vegetables require surface applications of waxes and water-loss barriers. This paper reports the research and development of an efficient electrostatic spray application method and processing-line prototype created specifically for postharvest protection of foodstuffs. In addition to relevant aspects of theoretical and technical design, the paper includes experimental results of extensive evaluations of electrostatically applied protective sprays onto bananas for international shipment – where both microbiological and mass-transfer data document typically 2.1-3.4 fold deposition improvements for food protection.

I. INTRODUCTION

To provide year-round supplies of many types of fruits and vegetables, extended periods of storage and shipment from opposite hemispheres are necessary. Such foodstuffs are subject to a wide variety of spoilage microorganisms which degrade the food directly by rot or reduce its palatability by introducing offensive taste or other objectional organoleptic characteristics. Damage results from numerous fungal and other microorganisms on food surfaces including, for example, *Fusarium spp.*, *Verticillium spp.*, *Acremonium spp.*, *Pseudomonas fragi*, *Erwinia carotovora*, *Leuconostoc dextranicum*, etc. Additionally, the mycotoxins naturally produced and expelled by certain microorganisms contaminating stored crops render the food unsafe for human consumption (e.g., the highly carcinogenic aflatoxins produced by *Aspergillus flavus* and *Aspergillus parasiticus* on stored peanuts, corn, etc.). Control measures by chemical, biological and physical means are routinely used to reduce food losses attributable to spoilage microorganisms and preclude mycotoxins. Controlled-atmosphere storage modifies the temperature, humidity, and gaseous composition within storage and shipping containers to conditions arresting the growth of harmful microorganisms. Where feasible, chemical fumigation

is relied upon for inactivating surface molds and other food-borne pests within air-tight enclosures. Often, however, postharvest foodstuffs such as fruits and vegetables must be treated openly at some stage along the processing or packing line prior to shipment. Aqueous solutions or suspensions of fungicidal control agents are commonly sprayed by pressure nozzles onto the product for this purpose. Such spray applications utilizing hydraulically-atomized droplets of typically 300-600 μm volume median diameter are characterized by poor surface coverage, inefficient droplet deposition, and excessive rebound and runoff of spray liquid. Improvements are demanded based upon economic, environmental, and product-quality considerations.

In recent years numerous agricultural spray applications have benefited by incorporating droplet charging and electrostatic deposition of pneumatically-atomized sprays onto biological crop surfaces [1]. The objective of this paper is to report the research, development and evaluation of an air-assisted, induction-charging, electrostatic spray-application method and processing-line prototype created specifically for efficiently applying anti-fungal agents and other protective coatings onto foodstuffs in an environmentally sound manner. Evaluations based upon both laboratory mass-transfer experiments and on-line microbiological assessments are presented to document, respectively, the deposition efficiency and the microorganism-control efficacy of the improved electrostatic-application process under ideal and real-life settings.

II. PROCESS AND PROTOTYPE DEVELOPMENT

In numerous commercial, industrial and agricultural spraying operations, electrostatic forces of attraction reliably increase the deposition of charged particulates onto target surfaces while minimizing off-target losses. Such operations include liquid and powder paint coatings, electrostatic precipitation of air pollutants from stacks, electrostatic spraying of agricultural pesticides [2] and pollen [3] onto field crops and orchards, xerographic copying, ink-jet printing, textile flocking, etc. Common to all these electrostatics-based operations for particulate control are: first, imparting an appreciable net electric charge onto the individual droplets or powder particles (e.g., 5-15 mC/kg charge-to-mass); and, secondly, propelling

the charged particulate to target surfaces by interaction with applied or self-imposed electric-fields. Figure 1 theoretically summarizes, as a function of diameter of particles having specific gravity 1.0, the effectiveness of three distinct type electric fields which may be exploited for electrostatic trajectory: a) induced image-charge; b) externally applied field; and c) the particulate-cloud's inherent space-charge field. As seen for charged particulates smaller than 100 μm diameter, both the space-charge field and applied field more rapidly drive the particulates as compared with gravitational and image-charge forces. Personnel safety considerations often preclude electric fields applied by metallic electrodes; thus, self-generated space-charge fields are conveniently relied upon in many less controllable settings such as crop spraying and with inexperienced process-line workers.

Figure 2 depicts a pneumatic-atomizing, electrostatic-induction, spray charger of the type used in this study (Electrostatic Spraying Systems, Inc. – MaxCharge™ model).

Typically these nozzles exhibit a 10-12 $\mu\text{C}/\text{kg}\cdot\text{V}$ linear spray-charging response vs. input voltage over a 200-1200 Vdc range [4]. Additionally, this pneumatic nozzle design incorporates ~5-6 m/s air-carrier velocity to aid penetration of 3-dimensional targets exhibiting Faraday shielding.

Figure 3 shows the prototype electrostatic sprayer unit developed utilizing an oscillating array of these air-assisted induction-charging nozzles for postharvest treatment of fruits and vegetables on processing and packing lines. As utilized in banana packing, for example, a 1 m x 1 m shallow plastic tray

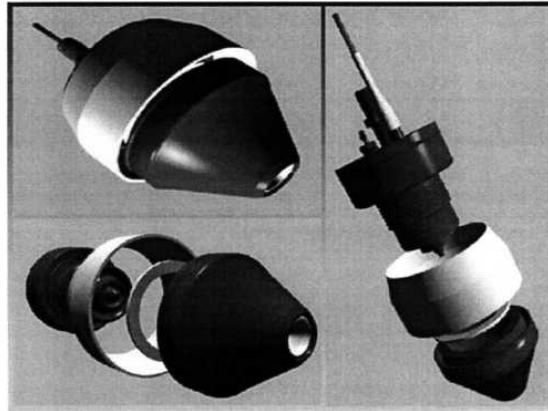


Fig. 2. Air-assisted electrostatic-induction spray-charging nozzle.

containing 16-18 clusters of 5-7 bananas each is pushed along the process roller-line into the treatment chamber ejecting the previously treated tray of fruit. Following a brief automated application of charged fungicidal spray, the cycle is repeated. The engineering design incorporates operational and safety features including: five charging nozzles (Fig. 2) mounted perpendicularly to a horizontal supply pipe which rotates ~100° back and forth about its axis at ~1.5 radian/s to sweep the spray over the treated product passing by ~75 cm below; pneumatic actuators which automate the system for safe and consistent operation; a well agitated liquid supply reservoir and transfer pump to maintain wettable-powder chemical agents in suspension; and a dielectric treatment chamber to minimize non-target deposition.

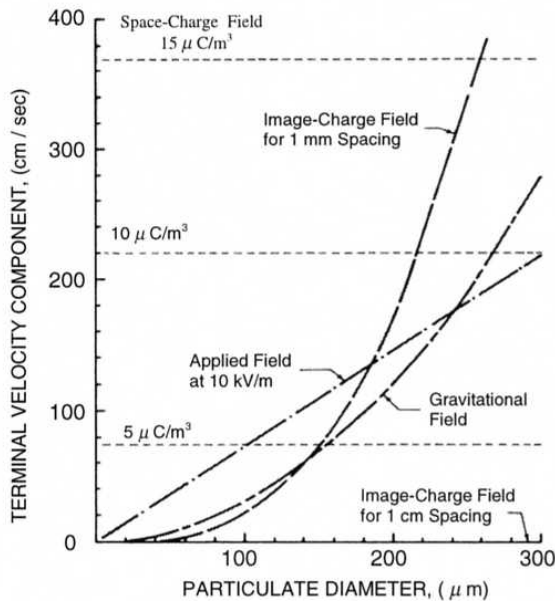


Fig. 1. Terminal velocities typically imparted to charged particulates by various force fields. (Sp. gr. = 1).



Fig. 3. Electrostatic spray chamber for postharvest application of protective sprays onto fruits and vegetables.

III. EXPERIMENTAL EVALUATIONS

The prototype electrostatic applicator for postharvest protective sprays has been extensively evaluated both on an engineering basis by fluorometric analysis of the deposition of tracer-tagged sprays onto fruits, and by microbiological assessment of actual postharvest disease control.

A. Laboratory Mass-Transfer Tests

Processing-line conditions for a banana packing house were simulated using the electrostatic spray-application unit shown in Fig. 3. Fifteen clusters of ethylene-ripened bananas (5-6 per cluster) were selected in sets of matched morphology. Small deposition targets were affixed to 4-5 specified disease-prone locations on 2-3 clusters which were randomly positioned among the 15 clusters on the spray tray and slid into the spray chamber where either a charged or uncharged spray treatment was randomly applied. Following each 2 s treatment (16 mL spray liquid), the tray was removed and the deposition targets carefully detached with forceps. To reclaim the collected spray tracer, the targets were placed into small polypropylene screw-cap bottles containing wash solution and tumbled 15 min. The concentration of fluorescent tracer in the target wash, and hence the nanograms mass of tracer on each target, was quantified by fluorometrically. Calibration against standards allowed linear correlation ($R^2 = 0.999$) of fluorometer units to nanograms of tracer mass, and then to ng/cm^2 areal deposition density of tracer on specified target surfaces.

All laboratory tests utilized a standardized tracer-tagged spray liquid developed in previous mass-transfer studies [5]. A 1.5 g portion of solid Day-GLO[®] Blaze Orange fluorescent pigment (GT-15-N) of 3-4 μm diameter and 1.37 specific gravity was suspended in 1 L of deionized water containing 0.1 g NaCl and 1.0 mL of non-ionic Triton X-100 surfactant. Characteristic spray-liquid physical properties at 25°C were: 21.7 mS/m conductivity, 32.9 mN/m surface tension, and 1.01 mPa·s viscosity.

Because naturally occurring contaminants on surfaces of banana peels introduced varying levels of background signal into fluorometer readings, small thin target surfaces were attached directly to the fruit by a conductive pin pushed into the fruit. Two series of spray-deposition experiments were then conducted – the first using 2.4 cm x 9.0 cm stainless steel targets, and the second utilizing 2.5 cm x 3.6 cm plastic targets. These two extreme target-conductivity conditions were intended to bracket the surface conductivity values exhibited by various fruits and vegetables as dependent upon the degree of waxy cutin present and, hence, verify the electrostatic-deposition benefit achievable under both conditions encountered in practice. Negligible fluorometer background signal was verified following standard washes of each type clean target.

Spray-Visualization Results - Figure 4 qualitatively documents the dramatic increase in spray migration toward banana clusters, especially the crown and neck regions, directly

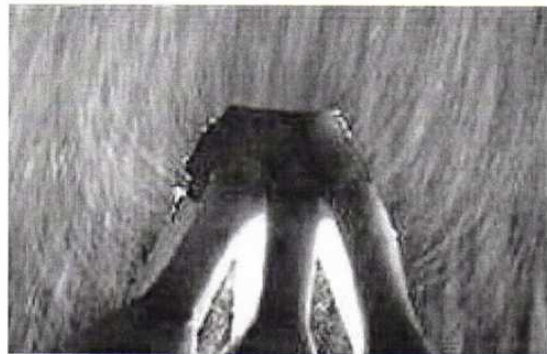
attributable to electrostatic attraction. This enhanced deposition pattern is quite significant for effectively controlling spoilage microorganisms which multiply in the latex exudate on the cut crowns. The pictured electrostatic wraparound and air-assisted penetration of finely atomized charged droplets in the neck region are also beneficial in providing the more thorough coverage needed for increased fungicidal efficacy.



Uncharged spray



Charged spray



Charged spray onto crown

Fig. 4. Electrostatic attraction of charged spray onto bananas.

Metal-Target Results - For these tests metal targets were attached onto each of two clusters per tray in the following locations: a) crown top, b) side of peel, c) between necks, and d) under the distal tip. The average deposition values for six replications of charged and uncharged spray treatments are given in Table 1 along with the Electrostatic Benefit ratio values of charged divided by uncharged deposition readings. By analysis of variance (ANOVA) of the data and Duncan's Multiple Range Test (DMRT), statistically significant increases in the mean values for charged-spray deposition could be declared ($\alpha = 0.05$) for all target locations except that Under Tip. Deposition on the disease-prone Crown increased 3.4-fold for charged vs. uncharged spray treatments; there were respectively 1.7- and 2-fold increases on the Side Peel and the Inside Neck regions. Figure 5 graphically summarizes charged and uncharged spray deposition mean values measured at the four target locations on banana clusters.

Plastic-Target Results - In these tests, which concentrated on wraparound deposition onto the crown region, a plastic target was pinned to the front, top, and rear surfaces of the cut crowns of three clusters of bananas in each tray. The average deposition values for six replications of charged and uncharged spray treatments are given in Table 2 along with Electrostatic Benefit ratio values. By ANOVA of the data and DMRT,

TABLE 1. MEAN VALUES OF SPRAY TRACER DEPOSITED AT INDICATED LOCATIONS ON BANANAS BY CHARGED AND UNCHARGED SPRAY APPLICATIONS.

Spraying method	Tracer deposition ¹ , (ng/cm ²)			
	Crown	Side Peel	Under Tip	Inside Neck
Charged	1513 a ²	473 a	355 a	706 a
Uncharged	452 b	276 b	241 a	357 b
Electrostatic Benefit ratio	3.4	1.7	1.5	2.0

1 Stainless steel targets

2 Means with same letter in same column are not significantly different ($p < 0.05$).

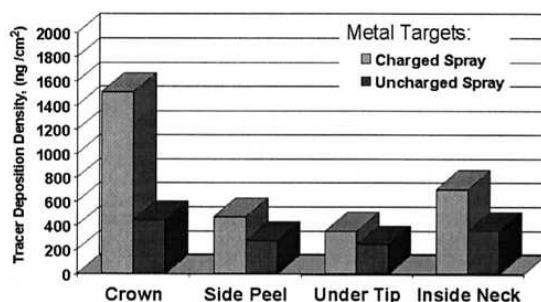


Fig. 5. Spray-tracer deposited onto indicated locations on bananas by charged and uncharged spray application methods. (Metal targets).

statistically significant increases in the mean values for charged-spray deposition could be declared ($\alpha = 0.05$) for all three crown locations. Electrostatic attraction increased by 2.1-fold the overall deposition onto the crowns. Furthermore, by comparing coefficient of variability (cv) values, charged spray deposition was less variable ($cv = 0.32$) among the three surfaces of the crown than was uncharged spray deposition ($cv = 0.74$). Additionally, charged spray deposition was less variable between cluster locations within a tray and treatment replications. Figure 6 graphically summarizes charged and uncharged spray deposition mean values measured at the three crown-surface locations on banana clusters.

Comparisons were also made of the amount of electrostatically applied spray-tracer deposited on plastic targets and that coating similar targets dipped into unatomized spray-tracer liquid. This simulated the common practice at many packing houses of immersing banana clusters into a vat of fungicidal liquid. To correspond with the high-volume dips used, 10 mL of the standard concentrated spray-tracer liquid was stirred into a beaker containing 140 mL of deionized water. Following immersion of a plastic target, an identical

TABLE 2. MEAN VALUES OF SPRAY TRACER DEPOSITED AT INDICATED LOCATIONS ON BANANA CROWNS BY CHARGED AND UNCHARGED SPRAY APPLICATIONS.

Spraying method	Tracer deposition on crown ¹ , (ng/cm ²)				SD ²	cv ³
	Top	Front	Rear	Overall		
Charged	2556 a ⁴	2080 a	1997 a	2211 a	430	0.32
Uncharged	1203 b	1081 b	809 b	1031 b	459	0.74
Electrostatic benefit ratio	2.1	1.9	2.5	2.1		

1 Plastic targets

2 Standard deviation

3 Coefficient of variability

4 Means with same letter in same column are not significantly different ($p < 0.05$).

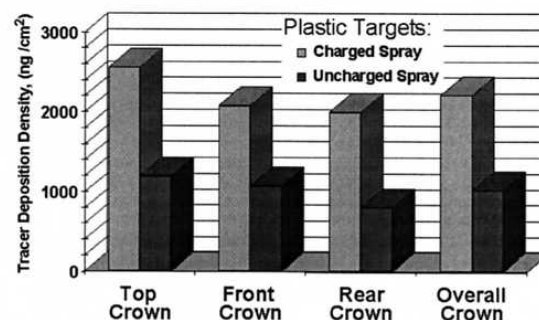


Fig. 6. Spray-tracer deposited at indicated locations on banana crowns by charged and uncharged spray-application methods. (Plastic targets).

fluorometric analysis determined spray-tracer retained on one side of the target. The dipped mean value of 80 ng/cm² compared with a mean value of 2211 ng/cm² measured for a similar target area electrostatically sprayed with finely atomized charged droplets.

B. Microbiological Tests

Efforts by the Rainforest Alliance and other environmental groups have encouraged a reduction in the use of postharvest fungicides commonly relied upon to control spoilage by rot during banana storage and shipment. One of the authors (*viz.*, S.C. Cooper) has installed electrostatic spray-application chambers (Fig. 3) in a number of Central American commercial banana packing houses and technically collaborated with M. Madrid and F. Lopez to microbiologically evaluate their efficacy at reduced chemical rates for controlling common spoilage microorganisms under real-life conditions [6]. Following washing and initial latex removal, clusters of 6-8 bananas each were inoculated with a 24×10^4 spore/mL suspension (complex of *Fusarium spp.*, *Verticillium spp.*, and *Acremonium spp.*) to ensure a challenging pathogen infestation and placed on plastic trays for fungicidal spray treatment. Conventional hydraulic-sprays were applied in an enclosed chamber at the usual chemical active ingredient (a.i.) rate of 100 mg imazalil and 100 mg thiabendazole in 250 mL total spray per 18.5 kg tray of bananas (corresponding to typical packed-box weight). Electrostatic sprays were applied at slightly less than half-rates a.i. of fungicide chemicals (48 mg imazalil and 48 mg thiabendazole) in only 16 mL total spray per 18.5 kg tray of bananas. A control treatment receiving inoculation but no fungicide was included. Replicated applications using 70 clusters per treatment were made and the treated bananas stored 26 days under temperature and atmospheric conditions simulating shipment and ethylene ripening.

Table 3 shows the percent incidence of postharvest rot within each of the five levels of severity which was visually evaluated at 26 days. Even at "half-rate" chemical applied in only ~ 6% total spray volume as compared with the

TABLE 3. PERCENT INCIDENCE OF POSTHARVEST ROT WITHIN EACH OF FIVE LEVELS OF SEVERITY VISUALLY DETECTED ON BANANAS STORED 26 DAYS FOLLOWING INDICATED FUNGICIDAL-SPRAY TREATMENT [6].

Fungicidal spray treatment	% Clusters exhibiting crown rot					% Other rots		
	No Rot	Trace	Light	Medium	Severe	Tip	Peel	Neck
Conventional (full-rate a.i.) ¹	74	20	6	0	0	3	9	7
Electrostatic (half-rate a.i.)	86	6	0	0	0	1	0	0
Control (zero a.i.)	36	39	13	8	4	6	15	8

¹ Full-rate a.i. per 18.5 kg bananas = 100 mg imazalil + 100 mg thiabendazole.

conventional treatment, the electrostatic treatment provided superior postharvest disease control; there were 86% crown-rot-free banana clusters vs. 74% conventional and 36% control rot-free. Similarly, the incidence of rot at all other banana locations was only 1% electrostatic vs. 19% conventional and 29% control.

IV. CONCLUSIONS

Electrostatic forces of attraction have been incorporated to provide an improved method for efficiently applying protective sprays onto postharvest fruits and vegetables. An oscillating array of air-assisted electrostatic-induction droplet-charging nozzles has been successfully designed into a dielectric chamber to each atomize and charge 1-2 mL/s flows of conductive liquid to typically 5-10 mC/kg charge-to-mass using only 500-1200 Vdc. As safely utilized on food processing and packing lines, 1 m² trays of 15-20 kg of fruits and vegetables are usually treated with 15-20 mL of finely atomized charged spray in ~2 s corresponding to a maximum continuous process-line speed of approximately 0.5 m/s or 260 metric tonnes throughput per 8 h workday.

Fluorometric evaluations of tracer-tagged spray (0.15% wt. concentration) onto bananas in laboratory tests verified that electrostatic forces increased tracer deposition a maximum of 3.4-fold from 452 to 1513 ng/cm² onto the disease-prone crown region for charged vs. uncharged spray applications. Microbiological assessments conducted on-site documented electrostatic applications of fungicidal sprays onto bananas provided better control of Costa Rican crown-rot fungal complex than conventional hydraulic sprays while using only half the fungicide chemical dispensed in only 6% the volume of spray. Additionally, the retention of tracer electrostatically deposited as finely atomized droplets was 27-fold greater than by the dip method. Environmental and economic benefits of postharvest protection by the electrostatic application method are thus confirmed.

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