Relevance of electrostatic forces in natural and artificial pollination

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Gan-Mor, S., Schwartz, Y., Bechar, A., Eisikowitch, D. and Manor, G. 1995. **Relevance of electrostatic forces in natural and artificial pollination**. Can. Agric. Eng. 37:189-194. The transfer of pollen grains from anther to stigma during natural pollination, particularly during hybrid seed production, is of interest to agricultural engineers. Artificial pollination to improve the yield and the quality of various fruits and vegetables is already in commercial use. Electrostatic forces, utilized by the honeybee in natural pollen detachment, were investigated in order to improve the design of future systems for artificial pollen detachment. Measurements showed that the average charge on a bee after active flight through the air was 23.1 pC, with a maximum of 93 pC. The forces required for detaching pollen were 4×10^{-10}, 3×10^{-10}, and 39×10^{-10} N for avocado, eucalyptus, and lizianthus, respectively. Mathematical modelling showed that there are cases when the accumulated charge on a honeybee is sufficient for non-contact pollen detachment.

Les ingénieurs ruraux s'intéressent au transfert des grains de pollen des anthères aux stigmates durant la processus de pollinisation, particulièrement lors de la production de semences hybrides. La pollinisation artificielle qui favorise l'augmentation de rendements et améliore la qualité de divers fruits et légumes est déjà utilisée commercialement. Les forces électrostatiques qui permettent à l'abeille de détacher le pollen de la fleur ont été étudiées afin d'améliorer la conception des futurs systèmes artificiels de détachement du pollen. Les mesures ont montré que la charge moyenne d'une abeille ayant volé activement dans l'air étaient de 23.1 pC, atteignant un maximum de 93 pC. Les forces requises pour détacher le pollen de la fleur étaient de 4×10^{-10}, 3×10^{-10} et 39×10^{-10} N pour l'avocat, l'eucalyptus et le lisianthus, respectivement. Des modèles mathématiques ont montré que dans certains cas les charges accumulées par l'abeille sont suffisantes pour détacher le pollen sans qu'il n'y ait contact.

INTRODUCTION

Commercial crops which are neither wind pollinated nor spontaneously self-pollinated, require an animal (usually an insect) to convey pollen from anther to stigma to produce fruits or seeds (Free 1993). Parthenocarpic crops do not require pollination since they produce seedless fruits. Lack of such a vector, or insufficient pollination, can result in poor or malformed fruits. In many cases, inadequate pollination is an outcome of unsuitable ecological conditions for both the plant and the pollinator. Such conditions can be low temperature, high humidity, rain, or fog (Corbet 1990; Michael 1994; Thorp 1979). Some restraints on pollination might also result from poor synchronization between pollen availability and stigma receptivity (Ish-Am and Eisikowitch 1991).

Production of hybrids, which demand bridging between the two different parent lines, increases the restraints on pollination since in this case pollinators tend to forage on a single line and not to switch from line to line (Eisikowitch and Loper 1984; Waller 1975). Pollination of hybrids, particularly for seed production of onions, anemones, tomatoes, etc., is generally a new responsibility for agricultural engineers. However, artificial pollination is already practiced to improve yield and quality of several fruits and vegetables. The development of new technologies for pollen transfer is thus desirable to reduce high production costs, to overcome the lack of appropriate pollinators, and to improve yield. Such developments would also facilitate hybrid seed production in additional ranges of agriculture.

Non-contact processes such as vibration and application of drag forces are used for artificial pollen detachment, but since they require a massive manual labor input, a better method is required. Electrostatic forces are not yet in use for artificial pollen detachment, but their potential should be investigated since experiments have shown that these forces can contribute to the detachment in natural insect pollination. Corbet et. al. (1982) showed that a dead honeybee connected to a potential of 750 V can cause detachment of oil-seed rape pollen from a grounded anther and cause it to jump across an air gap of 0.63 mm. Under the same potential, this pollen jumped across a gap of 0.376 mm from a charged bee to a grounded stigma.

Electric charges generated by honeybees have previously been evaluated by Erickson (1975) and by Erickson and Buchmann (1983). Their experimental device comprised two concentric conductive tubes, 5 mm long, with an outer diameter of 12 mm and a 2 mm gap between them. As each bee walked through the inner tube on entering the hive, it raised the potential between the tubes by an average of 1.8 V. Simple calculation for this geometry shows that each bee was transferring an average charge of 12 pC (12×10^{-12} Coulomb) while passing through the tube. This procedure, however, involved full contact between the bee and the measuring device, which would result in a lower reading than the true value. In addition, because of the nonconductive nature of most of the bee's surface, it is safe to assume that a substantial portion of its charge was not transferred during the passage through the tube. Consequently, the charge measured by this technique is probably a lower bound of the true value.

Yes'kov and Sapozhnikov (1976) measured the bee charge directly and found values of up to 45 pC per honeybee. Both of the above charge values correspond to potentials of a few hundred volts when the bee geometry is considered. Direct measurements of potentials were made by Warnke (1976) who found values of 450 V at certain locations on the bee's body. Since most parts of the bee's surface have high impedance and since its geometry is elongated, all of the above techniques should provide data only for local charges and are likely to provide lower bounds for the charge and potential values.

Hardin (1976) suggested that since most stigmas stick out of the flower and have low impedance, an approaching charged body will cause a strong electric field around the stigma. Such a field may enhance pollen transfer from the bee to the stigma.

Strong wing flapping of bees is frequently reported in the literature as a cause for a massive pollen transfer from the anther to the bee, prior to any contact. This wing flapping is referred to as "buzz pollination" (Buchmann 1983) and it might be indicative of the bee's ability to control the charge it generates and accumulates.

The objective of the present work was to construct a non-intervening technique for measuring the electric field induced by a charged honeybee and, with the help of measurements of the force required for detaching pollen grains, to calculate the distance through which non-contact detachment of pollen can take place. Better understanding of pollen detachment in natural processes could improve the design of future systems for artificial pollen detachment.

EXPERIMENTAL APPARATUS AND BASIC EQUATIONS

Two different sets of experiments were performed to determine whether a honeybee can detach pollen by means of electrostatic forces only. The first set was aimed at measuring the charge on the bee; the second was designed to measure the force required for detaching the pollen from its cluster.

Non-intervening measurements of the bee charge

The bee charge was measured in this work without any contact to avoid the measurement of only a local charge, because of the low conductivity of the bee surface. To determine how the honeybee accumulates electric charge and to measure the value of that charge, two tests were conducted. The first involved a passive passage through the air with no wing flapping and the second involved an active flight.

In the first test, a honeybee was paralyzed by a freezing shock and swung in a circular motion by an electric motor mounted on top of the rig shown in Fig. 1. In the second test, the bee was allowed to fly but was tied to the rig top with a cotton thread. In both cases the bee was caught outside the hive on the morning of the experiment, to ensure capture of a foraging bee. Then, it was cooled for several minutes to reduce its activity and to allow a 300-mm-long cotton thread to be tied between its chest and abdomen.

In the passive experiment, an electric motor swung the bee.

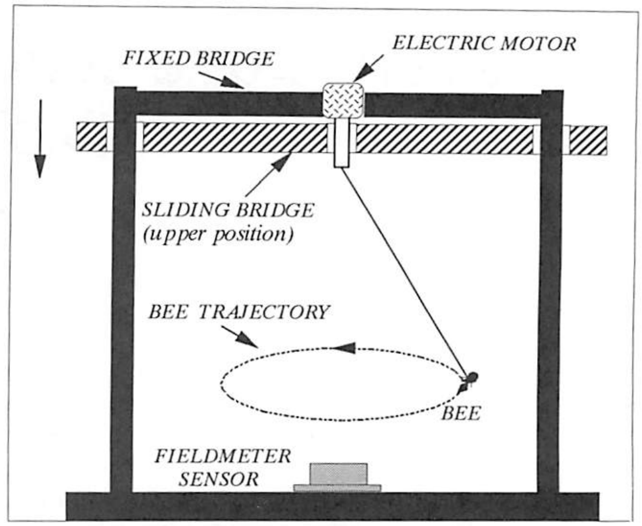

Fig. 1. Experimental setup for measuring the charge generated by bees after a passive rotation by an electric motor or after active flight. The bridge is raised to permit motion through the air.

In the active flight experiment, the bee was allowed to fly naturally for 3 minutes while connected to the thread. At the end of the flight the bee was placed near an electric field meter for a couple of seconds until the measurement was recorded. Fig. 2(a) shows the sliding bridge in a lower position, holding the bee 3 mm above an electrostatic field meter (Model 245, Monroe Electronics Inc, Lyndonville, NY). The bridge was made of acrylic and its lower surface was 14 mm above the field meter, causing less than 1% average reading error. The device measurement range was 0 - 1000 V/mm, with a sensitivity of 0.2 V/mm and a 1 s response time. The test included 9 bees for the passive experiment and 11 for the active one. Three replications were conducted for each bee.

The time that elapsed from the termination of flight to completion of the measurement was less than 3 s. There was negligible charge leakage during this time, since the relaxation time of the cotton thread at the prevailing temperature and humidity is longer than 8 s (Fink 1982). The charge relaxation time is defined here as the time taken for the charge to drop to 1/e of the initial charge. The relaxation time for charge leakage through the air under these conditions is even longer.

The distance between the center of the charged body and the electrostatic field meter is of particular importance for determining the charge on the bee's body. The average length of a honeybee is 13 mm and its body could be described as an axisymmetric with an average diameter of 5 mm. Since the body is frequently not stretched and for ease of computation, a spherical shape of equivalent surface area was selected. The diameter of the equivalent sphere was 8.8 mm. The average distance between the sensor and the center of the model bee was 7.4 mm (Fig. 2(b)). Then, the charge on the bee (or equivalent sphere), Q_b, can be found from:

$$Q_b = 4 \pi \varepsilon_0 E r^2 \qquad (1)$$

20°C and relative humidities of 30 and of 70%.

The above calculations provide a lower-bound solution. The actual electrostatic forces are probably higher, since the measurements were taken approximately 1.5 s after each flight and, therefore, after some charge leakage. In addition, a nonuniform charge distribution on the bee enables it to approach the pollen with a section that has a higher charge level.

The charge induced by a charged bee on a pollen grain located on a flower was calculated with the aid of the "successive approximation of images" technique (Corson and Lorrain 1962). Figure 3 compares experimental and calculated charge values induced on a grounded sphere by a disk of a predetermined potential. The experimental charge values were measured by a Kaithly electrometer and the calculated values were determined with the aid of the "successive approximation of images" technique. The relationship between the forces induced on a pollen grain by a charged bee and the distance between the two is discussed below in detail. The solution considers both the bee and the flower as conducting spheres, with the flower grounded and the bee having a certain charge. The charges on the bee and the flower were used to determine the electric field and the force acting on the pollen grain.

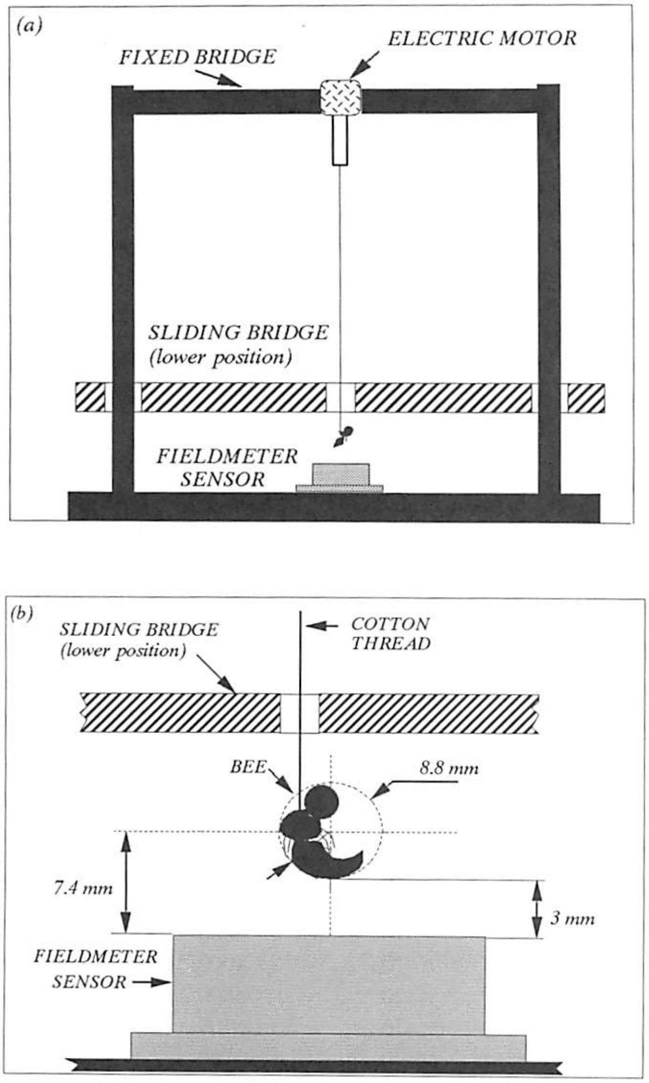

Fig. 2. Experimental setup for measuring the charge on a bee; the bridge is lowered to retain the bee above the field meter during the measurement. (a) General view and (b) the geometrical arrangement of the bee and the field meter.

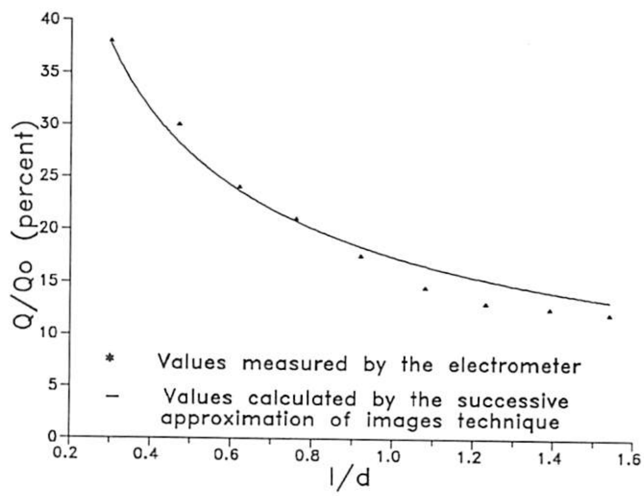

Fig. 3. The charge induced on a grounded sphere by a disk at a predetermined potential vs the distance between them. Q is the charge on the sphere, Q_o is the charge on the disk, d is the disk diameter and l is the distance between them. The charge was calculated with the aid of the "successive approximation of images" technique.

where:

r = distance from center of sphere to measured point,

ε_o = dielectric constant in a vacuum (approximately that of dry air), and

E = electrostatic field strength at measured point.

The capacitance of the sphere, C, is (Moore 1973):

$$C = 4\ \pi\ \varepsilon_0\ r_s \qquad (2)$$

where r_s = sphere radius. For an 8.8 mm sphere the capacitance is 0.49 pF.

The potential on the bee surface, V, for a uniformly distributed charge is:

$$V = Q_b/C \qquad (3)$$

All the measurements were taken at a room temperature of

Measurements of the detaching forces

The force required to detach a pollen grain from its cluster was determined by applying a series of known electrostatic forces to the grain until it was detached.

The experimental system comprised an insulated box in which a holder for a flower or an anther was located. The holder was grounded and had a conductive clamp mounted on a slide which enabled the distance between the anther and an electrode to be adjusted. The electrode was connected to a 0-30kV DC power supply (Hipotronics, Inc., Brewster, NY).

Two types of electrodes were used to cross check the results. The first electrode was a flat 50 x 50-mm metal plate. The second electrode was a 4-mm-diameter metal pin within a 1-mm-thick insulating layer. The force required to detach a pollen grain was found experimentally by gradually increasing the electrostatic field in the flower zone. The field was increased either by increasing the potential or by decreasing the gap between the electrode and the anther.

The detaching force acting on a particle located at the tip of a grounded pin is a result of a phenomenon called induction charging, in which a charged body induces a charge of the opposite sign on the tip of the grounded object. Figure 4 shows the system for measuring the detaching force when a pin electrode held at a predetermined potential induces a charge on a flower tip where pollen grains are located.

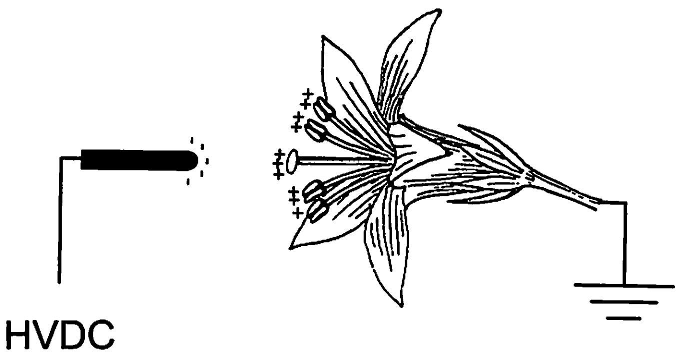

Fig. 4. The system used for determining the detaching force imposed by a pin electrode hooked to various potentials. The scheme illustrates the mechanism of inducing charge and exerting force on a grounded object.

The forces were calculated from the measured fields as follows. The charge induced on a pollen grain by the plate was calculated with the aid of the "successive approximation of images" technique (Corson and Lorrain 1962). The solution considers the flower as a conductive sphere.

The charge induced on a pollen grain by the conductive pin was found by an empirical technique. The field value, E, at a certain point was measured and the charge, Q_p, induced on a pollen grain was calculated by (Cho 1964):

$$Q_p = 1.65\ (4\ \pi\ \varepsilon_0\ r_p^2\ E) \qquad (4)$$

where r_p = pollen grain radius.

If the values of the pollen grain charge and the electric field are known, the force, F, on a pollen grain is given by the basic equation $F = EQ_p$. Because of the small size of the pollen grain (typical pollen grain radius is 0.015 mm) and the moderate electric field gradient, the error in the calculated force due to the assumption of uniform charge distribution along the grain, is less than 1%. The maximal air gap across which a pollen grain could be detached was calculated from the force induced by the bee and the necessary detaching force. The detaching field and force were determined when the first mass of pollen departed from the anther.

Avocado and lizianthus were selected for these experiments because it seems that artificial pollination can improve fruit yield and quality for the first one and hybrid seed production for the second. Eucalyptus flowers were chosen because they are available almost all year round.

RESULTS AND DISCUSSION

The electrostatic field induced by a passive honeybee was measured with nine different bees, with three replications for each one. No measurable electrostatic field was induced by a honeybee after passive passage through the air. This result was also obtained for a honeybee that was left motionless. However, the electrostatic field reached values of up to 15.2 V/mm for a very dynamic bee after active flight through the air. The dynamic bee is characterized by fast flight, frequent changes in flight direction, and loud buzzing noise. Table I shows the average results of electric field and charge for each honeybee.

Table I: Measured values of the electric field induced by charged bees and the calculated charges

Bee number	Relative humidity (%)	Electric field (V/m)	Electric charge (pc)
1	30	800	4.9
2	30	1600	9.8
3	30	2000	12.2
4	30	2400	14.7
5	30	4000	24.5
6	70	4000	24.5
7	70	4000	24.5
8	70	4000	24.5
9	70	5600	34.3
10	70	6400	39.2
11	70	15200	93.0
Average*		3778	23.1
Std.*		1589	9.7

* Note: Average results - not including extreme values (bees no. 1 and 11).

The average field measured for the active flights was 3.78 V/mm, with standard deviation of 1.59 V/mm. As mentioned above and illustrated by Fig. 2(b), the average distance between the center of the bee and the sensor was 7.4 mm. Using this distance in Eq. 1 gives an average bee charge of 23.1 pC. Extreme results were rejected in calculating this average result. The maximum charge was 93 pC. Utilizing Eq. 3 provides an average potential on a bee of 46.7 V.

The high charge values measured after flight with wing flapping, in contrast to the zero charge measured when there was no wing flapping, suggests that the wing flapping enables the bee to exercise some kind of friction charging (tribo-charging). If the bee can control the charge it produces by wing flapping and since observations show that a foraging bee produces stronger wing flapping when approaching a flower (Buchmann 1983), the charges measured in the labo-

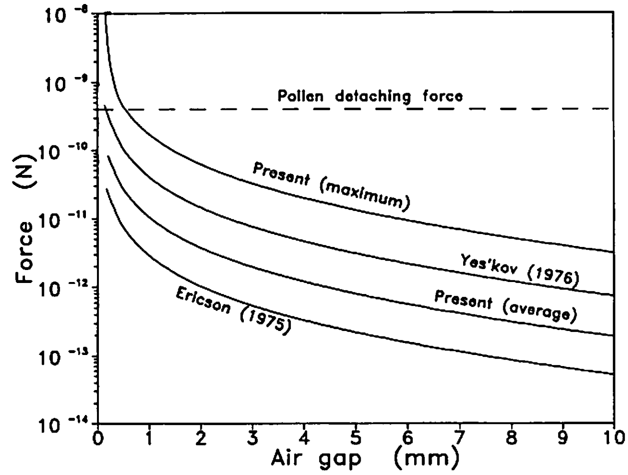

Fig. 5. Force induced on avocado pollen grain as a function of the distance from a charged bee. The forces were calculated by the "successive approximation of images technique".

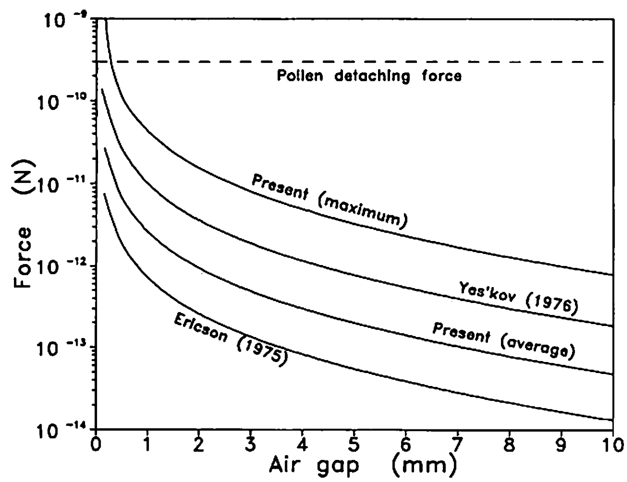

Fig. 6. Force induced on a eucalyptus pollen grain as a function of the distance from a charged bee.

Table II: Measurements of the electric field and the calculated forces required to detach lizianthus pollen grains

Experiment number	Potential (V)	Detaching distance (mm)	Electric field (V/mm)	Pollen charge (C)	Detaching force (N)
1	10000	20	305	9.5E - 15	2.9E - 09
2	15000	30	371	1.2E - 14	4.3E - 09
3	20000	40	404	1.3E - 14	5.1E - 09
4	25000	60	385	1.2E - 14	4.6E - 09
5	30000	120	293	9.1E - 15	2.7E - 09
Average			351.6	1.1E - 14	3.9E - 09
Std.			49.6	1.5E - 15	1.1E - 09

ratory conditions were probably only lower bound. As described above, the "successive approximation of images" technique was used to calculate the force induced on a pollen grain by a charged bee. This was a function of the distance between the grain and the modeled bee surface (Figs. 5 and 6).

The values found by Erickson (1975) and by Yes'kov and Sapozhnikov (1976) are for potentials. Information from the literature on the geometrical configuration and additional information (Erickson, E.H., USDA Bee Laboratories, Tuson, AZ) was used to calculate the capacitance of the measured body. The charge was determined from the basic equation $Q = VC$. The forces were then calculated as above and are presented in Figs. 5 and 6.

The forces required for detaching a pollen grain with electrodes were found utilizing the methods described above. The value for avocado flowers was 4×10^{-10} N, for eucalyptus flowers 3×10^{-10} N and for lizianthus flowers 39×10^{-10} N. The horizontal lines shown in Figs. 5 and 6 represent these detaching forces. At the distance that the force induced by the bee exceeds this value, electrostatic pollen detachment occurs. No-contact detachment is possible for a zero distance between the bee modeled surface and the pollen, in the common case where a honey bee curves its body when approaching a flower.

Examples of experimental results for detaching fields and forces are given in Table II for lizianthus pollen. The calculation of the maximal air gap across which a pollen grain could be detached was described above. The gap for avocado was 0.16 mm for the charge values found by Yes'kov and Sapozhnikov (1976) and 0.005 mm for the average result of the present work (Fig. 5). For eucalyptus flowers only the higher charge values were sufficient for pollen detachment (Fig. 6).

The ability of a bee to accomplish non-contact pollen detachment has been mentioned in the cited literature; it can now be related to the presence of an electrostatic charge. This charge on the bee seems to be caused by wing motion. All of the bee-induced forces shown in Figs. 5 and 6 were measured for non-foraging conditions. If a honeybee could control the rubbing motion of its wings, it would be expected to increase this during foraging, to produce higher charge levels when the benefit of increased pollen collection is expected.

The experiments described above show that due to their small size and other physical properties, pollen grains respond well to the electrostatic forces induced by honeybees.

The contribution of electrostatic forces for pollen detachment is being further investigated in continuing research aimed at the design, development, and testing of a pollen harvester.

SUMMARY AND CONCLUSIONS

Measurements of the electrostatic field induced by a honeybee after active flight through the air showed lower-bound charge values of 23.1 pC average and up to 93 pC maximum. No measurable charges were found after passive passage through the air or for stationary bees.

Electrostatic forces induced by various electrodes were found to be effective in detaching pollen. The electrode-induced forces required for detaching pollen grains were $4x10^{-10}$, $3x10^{-10}$, and $39x10^{-10}$ N for avocado, eucalyptus and lizianthus, respectively.

The measured values of detaching forces and bee charges indicate that a honeybee slightly more active than average could produce enough electrostatic force to detach avocado pollen grains. For eucalyptus, only a very active honeybee could generate enough charge for electrostatic pollen detachment.

Pollen grains respond well to electrostatic forces induced by honeybees. The natural application of this property could be mimicked and used by engineers in the design of a pollen harvester.

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