Insect exclusion screens: the size of the holes from a three-dimensional perspective

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Abstract

Insect-proof screens are considered as flat bodies. However, from a microscopic point of view a screen is not a flat body but, on the contrary, the spatial arrangement of the threads determines that the passage surface for an insect is larger than the one obtained in the measures made on images in orthogonal projection. This paper compares the effectiveness against *Bemisia tabaci* of different types of screens and perforated sheets. A perforated sheet has a negligible thickness and therefore, the comparison between these two types of physical barriers allows determining qualitatively the importance of the spatial arrangement of the threads on the efficacy of the screens. It also compares the efficacy between screens with similar hole widths to assess the validity of the "prison effect" as design criteria. The results show that if screens are used smaller holes (measured in orthogonal projection) are needed in comparison to the holes of the perforated sheets to obtain similar values of efficacy against the whitefly because the porous surface of the holes of the screens is not flat. The results also indicate that the geometry and the shape factor of the holes of both physical barriers must be similar to obtain a measure of the 3D surface of the holes of the screens. Screens with the same hole width have different efficacy against *B. tabaci*. The most critical hole region for the passage of the insects is the distance defined by the crossing of two consecutive warp threads. This separation divides the hole in two parts. Although this distance is sufficiently small so that the insect cannot pass if the hole is very elongated the insect could pass by one of the halves and for this reason the hole length of the holes also influences on the efficacy of the screens.

Keywords: *Bemisia tabaci*, perforated sheets, efficacy tests

INTRODUCTION

The efficacy of insect-proof screens how physical method of crop protection is sufficiently proven in numerous research papers (Berlinger et al., 1988, 1991, 1992; Baker and Jones, 1989; Roberts et al., 1995). There are many advantages obtained with its use. But protection screens also have a big drawback related to the resistance offered to the air flow. Their use considerably reduces the ventilation rate and produces imbalances in the microclimate with negative consequences for crop development (Teitel, 2001; Kittas et al., 2006). For this reason, screens must be designed with small size holes to avoid the passage of insects but with the limitation that the air flow is not drastically reduced. In short, it is a compromise solution: one of the goals at the expense of the other. For this reason we need to optimize the design of the insect exclusion screens. The structure of the weave of insect-proof screens is determined by two sets of threads (weft and warp) which interweave perpendicularly. The separation of the threads in each direction means that the geometry of each hole is rectangular, since the threads making up the warp are usually closer together than those of the weft. The number of threads per unit length establishes the density of threads of the screen in each direction. The thickness of the threads is another variable that define the geometry of the screen. These two parameters determine the dimensions of the holes of the screen. Regardless of other factors, the dimensions of the holes (width and length) obtained by considering only the density and thickness of the threads correspond to

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measures obtained on the orthogonal projection of the screen. However, from the microscopic point of view, a fabric is not a flat body but it responds to a three-dimensional structure. The warp threads "embrace" the weft threads and this determines that the porous surface is not flat but three-dimensional. Therefore, opening between the threads for the passage of insects is greater than that obtained on the measures on orthogonal projections. To evaluate the true size of the holes from a practical perspective we have performed laboratory tests where we compare the efficiency against *Bemisia tabaci* using different insect-proof screens (three-dimensional) and perforated sheets (flat). The equivalences between the exclusion percentage of screens and perforated sheets allow determining the real hole size of insect exclusion screens.

MATERIALS AND METHODS

Screens and perforated sheets

This study is based on a comparison of the results obtained in assessing the efficacy against the whitefly *B. tabaci* of a set of insect-proof screens and other set of perforated sheets. The evaluated screens are commercial fabrics and the perforated sheets are plastic sheets with micro-perforations used as food packaging (Figure 1). The geometry of the insect exclusion screens was measured by the protocol described by Álvarez et al. (2006), Álvarez (2010) and Álvarez et al. (2012). The physical barriers thickness was measured by a digital micrometre (Micromaster easy, TESA).

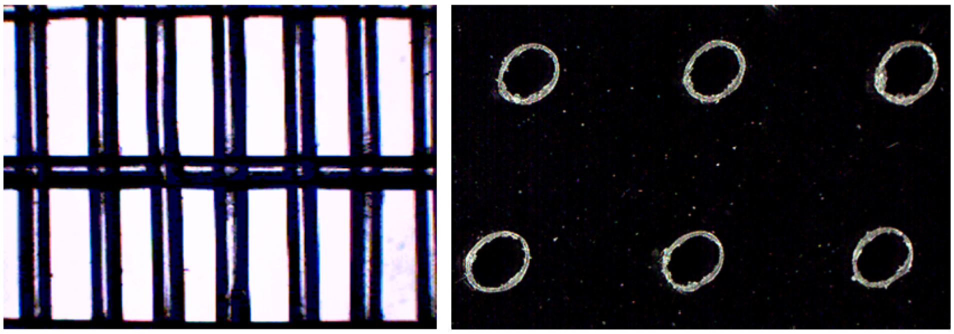

Figure 1. Screen (sc02) and perforated sheet (ps05).

The dimensions of the holes of the perforated sheets were measured on digital images (Figure 1) taken with a digital camera (Moticam 2, Motic) mounted on a stereo-microscope. The perforated surfaces were segmented from the rest of the image using a software for image editing (GIMP v2.8.14) and the major and minor axis of each hole and its surface were measured using a software for image processing (Image Tool v3.0).

The geometry of the holes of the physical barriers analysed is different. In the case of the screens the holes are similar to parallelograms and in the case of the perforated sheets the holes take the form of an ellipse (Figures 1 and 2).

Efficacy against *Bemisia tabaci*

The tests to determine the effectiveness of the insect-proof screens and perforated sheets were carried out under laboratory conditions according to the protocol described by Oliva and Álvarez (2013). Each test consists of three replicates and each of these repetitions lasted 24 h. The tests were carried out in calm conditions. The temperature were measured by a thermo-anemometer (HD29V37TC2, DeltaOHM) because its control is fundamental due to the great influence of this variable has on insect activity and therefore in the efficacy against the insects.

The efficacy of the screens has been calculated as the ratio between the number of individuals that did not get to cross the physical barriers and the total number of individuals introduced in the test device.

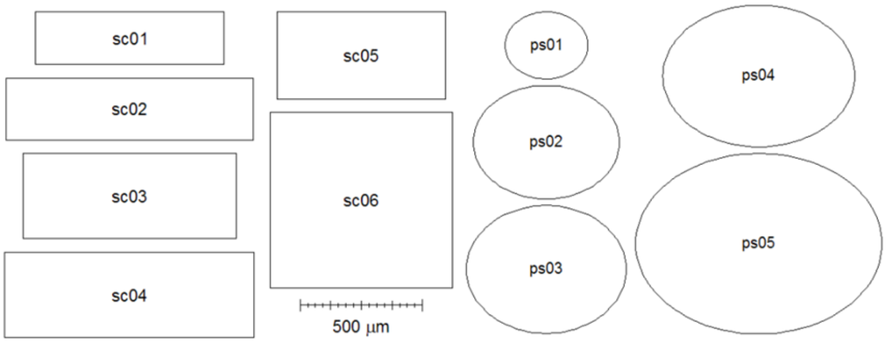

Figure 2. Comparative of the hole sizes of the screens and perforated sheets (orthogonal projection).

RESULTS AND DISCUSSION

Characteristics of screens and perforated sheets

The geometric characteristics of insect exclusion screens are summarized in Table 1 (800 holes of each textile were measured). These values provide information on the average number of threads per unit length $\rho_x \times \rho_y$ in weft and warp directions (density of threads), the average width $L_{sc,w}$ and length $L_{sc,l}$ of the holes, the average diameter of the threads D_{th}, the average surface of the holes S_{sc} and a shape factor that is obtained by dividing the width $L_{sc,w}$ between the length $L_{sc,l}$ of the holes and so when it is equal to 1 indicates that the geometry of the holes is square and when it approaches 0 indicates that the difference between width and length is large. The representation of hole sizes covers the range from 215.0 to 714.4 µm corresponding to efficacies of 100.0 and 3.6% respectively. The measures presented in Table 1 show how the smallest hole widths correspond to the highest densities of threads. The interval of hole lengths $L_{sc,l}$ of the six analyzed screens cover a range of values between 686.4 and 1018.1 µm. In this case cannot establish a correspondence between these values and the density of threads. This indicates that the variable that the manufacturers mainly have in mind with regard to the efficacy of their fabrics is the width of the hole and that they use the hole length according to the porosity values that they want to achieve.

Table 1. Geometric characteristics and efficacy of the insect exclusion screens.

Screen	$\rho_x \times \rho_x$ (threads cm^{-2})	$L_{sc,w}$ (µm)	$L_{sc,l}$ (µm)	D_{th} (µm)	S_{sc} (mm^2)	$L_{sc,w}/L_{sc,l}$	T (°C)	Efficacy (%)
sc01	9.9×20.9	215.0	770.3	253.0	0.166	0.28	22.4	100.0
sc02	8.0×20.2	252.7	1008.8	242.9	0.255	0.25	27.2	78.0
sc03	8.9×16.8	348.5	870.9	246.9	0.303	0.40	20.9	62.8
sc04	7.9×16.5	348.9	1018.1	255.2	0.355	0.34	25.3	12.0
sc05	10.5×16.3	355.1	686.4	259.9	0.244	0.52	21.1	71.6
sc06	9.8×9.8	714.7	741.8	295.3[1]	0.530	0.96	24.3	3.6

[1]Mean value between the thickness of the weft and warp threads (they are both slightly different).

The geometric characteristics of the holes of the perforated sheets are summarized in Table 2. In this case, only 20 holes were measured since the measurement process is not automated. The data presented are the average lengths of the major $L_{ps,Ma}$ and minor axes $L_{ps,Mi}$ of the holes, its average area S_{ps} and the ratio (shape factor) between the minor axis length and the major axis length that as it is closer to 1 indicates that the hole is circular and as it approaches zero indicates that is elongated (elliptical). The size range of minor axes belongs to the interval between 273.2 and 734.9 µm, i.e., it is similar to the interval of the hole widths of the screens. The interval related to the major axis of the holes is between 338.2 and 1005.1 μm. In this case, the interval is greater in comparison with the interval of the hole lengths of the screens because the lower limit is smaller. The thickness of the screens is around 500 μm and in the case of perforated sheets it is negligible. Considering the ratio between the minor and major axis lengths (greater than 0.7) of the perforated sheets it can be said that the entire surface of the holes is useful for the passage of insects. In the case of the screens the holes are elongated and the above does not occur. However, the ratio between the hole width and length of the screens is smaller and it can be said that not the entire surface of the holes is useful for the passage of insects (except in the case of sc06).

Table 2. Geometric characteristics and efficacy of the perforated sheets.

Perf. sheet	$L_{ps,Mi}$ (μm)	$L_{ps,Ma}$ (μm)	S_{ps} (mm^2)	$L_{ps,Mi}/L_{ps,Ma}$	T (ºC)	Efficacy (%)
ps01	273.3	338.2	0.069	0.81	25.2	100.0
ps02	461.2	596.8	0.203	0.77	26.2	75.1
ps03	520.5	651.8	0.237	0.80	26.7	79.7
ps04	576.5	784.2	0.277	0.74	24.1	59.2
ps05	734.9	1005.1	0.567	0.73	27.2	5.4

Efficacy according to the hole width

The relationship between the average sizes of the holes and the efficacy of the physical barriers is represented in Figure 3. The choice of the variable representative of the hole sizes has been the hole width $L_{sc,w}$ in the case of the screens and the hole minor axis $L_{ps,Mi}$ in the case of the perforated screens. The trend lines of both sets of data show a certain “parallelism” between them (Figure 3). Specifically, the trend line of perforated sheets is further from the x-axis. This means that if screens are used smaller holes (width) are needed. This assertion is made from the point of view of the measurements taken in orthogonal projection. In the case of perforated sheets these measures are real because the perforated sheets have a negligible thickness.

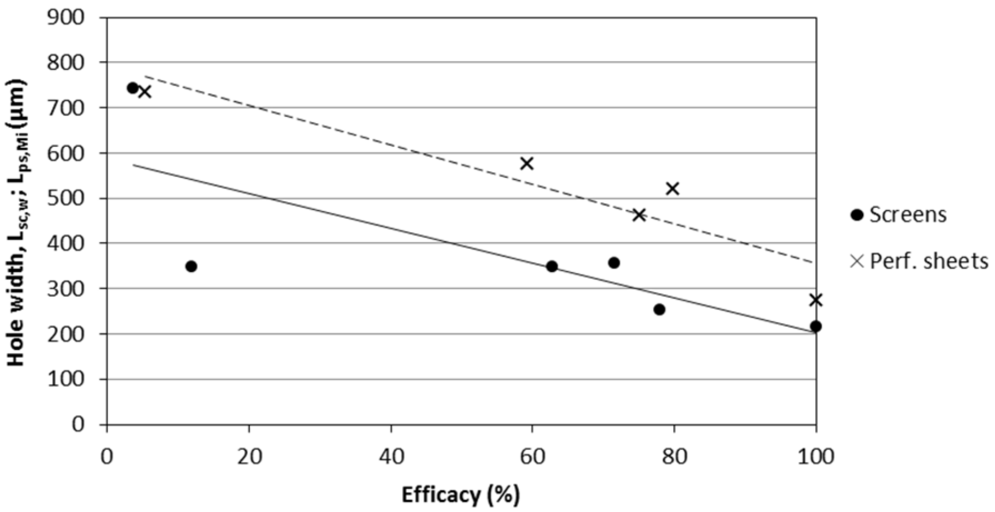

Figure 3. Relationship between the hole size ($L_{sc,w}$ and $L_{ps,Mi}$) and the screen efficacy.

Importance of the length of the holes

Apparently, some results are meaningless. This is the case of the efficacy measured for the sc03 and sc04 screens (Table 1). Both screens have a hole width $L_{sc,w}$ equal to 348.5 and

348.9 µm respectively. These distances measure the separation between the warp threads in the plane of the fabric. These hole widths define the theoretical efficacy of the screens which should be similar for both screens. However, the efficacies measured in the laboratory tests provide a value equal to 62.8% for the sc03 screen and 12.0% for the sc04 screen. In other words, there is a difference of more than 50 percentage points in the values of efficacy of both screens. Actually, it is a disconcerting fact. There are two factors that can influence this important difference, on the one hand the temperature (the difference of temperature of the tests performed to one and another screen was 4.4°C) and on the other hand the hole length (the difference is almost 150 µm between the two screens). In our experience, temperature is a variable that can explain this difference (Oliva and Álvarez, 2013) but it also raises the hypothesis that not only the hole width determines the efficacy of the screen: the hole length also influences the efficacy of the screen. If the sc05 screen is joined to the comparison between the two previous screens (sc03 and sc04) it can be seen as the hypothesis is fulfilled. The difference in separation of warp threads $L_{sc,w}$ between the sc03 and sc05 screens is 6.6 µm (negligible); the average temperatures to which was measured the efficacy of both screens differ in 0.2°C and, however, there are 8.8 percentage points of difference between the efficacy of both screens (taking into account that the sc05 screen is more effective against *B. tabaci* although it has a slightly larger hole size $L_{sc,w}$). Therefore, the differences in the hole lengths $L_{sc,l}$ (870.9 µm in the case of the sc03 screen and 687.4 µm in the case of the sc05 screen) also explain the discrepancies between the results obtained.

Figure 4 shows the relationship between the dimension of greater length of the holes of the two physical barriers (hole length $L_{sc,l}$ for the screens and major axis length $L_{ps,Ma}$ for the perforated sheets) and its efficiency against *B. tabaci*. It also represents the trend line that describes this relationship in the case of the perforated sheets. The trend line for the values related with the screens is not represented because the relationship is not consistent. The shape factor of the perforated sheets is in all cases greater than 0.7 and this establishes a logical relation between the major axis of the holes and the efficacy of the physical barrier. However, in the case of the screens the differences between the width and length of the holes are much larger and therefore there is no logical relationship between the hole length and the screen efficacy.

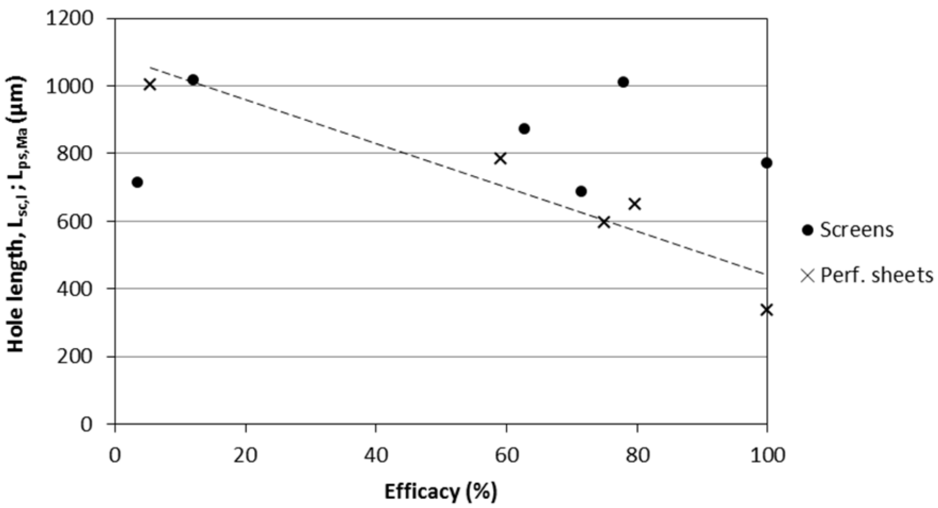

Figure 4. Relationship between the hole size ($L_{sc,l}$ and $L_{ps,Ma}$) and the screen efficacy.

Three-dimensional considerations

An insect-proof screen is a fabric that is not a flat body from a microscopic point of view (considering the dimensions of insects). The fabric structure is made up of two groups of perpendicular interwoven threads called weft and warp. The warp, in turn, also has two groups of threads that during manufacturing are separated alternately given rise to a separation through which a weft thread passes. In short, the end result is a woven structure in which the warp threads "embrace" the weft threads and that configures a three dimensional structure.

A hole of a screen is defined by considering the space left between two pairs of adjacent weft and warp threads (Figure 5). The warp threads cross in space and this distance is equal to the hole width $L_{sc,w}$ (dashed line in Figure 5). This separation is the most limiting distance for the entrance of *B. tabaci* but as the warp threads are separated in space they leave a porous surface that is greater than that which can be measured in orthogonal projection. Therefore, although this distance $L_{sc,w}$ is sufficiently small so that the insect cannot pass, if the length of the hole is large enough the insect will be able to pass through the gap left between the warp threads.

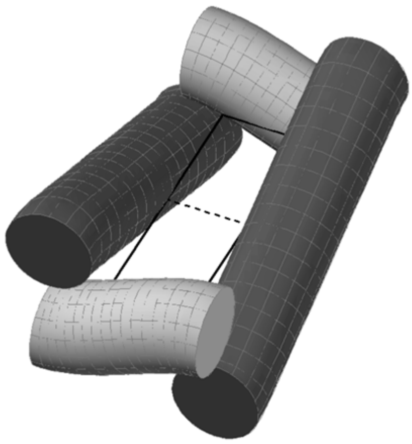

Figure 5. Three-dimensional representation of a screen hole. In dark grey are represented the warp threads. The black rectangle represents the hole in orthogonal projection.

According to the above, it is necessary to reconsider what in other works we have defined as "effect prison" (Álvarez, 2010). The effect prison (considering measures carried out in orthogonal projection) is a design criteria which establishes the theoretical efficacy of an insect-proof screen according to the separation of the warp threads, i.e., if the warp threads are sufficiently together the insect cannot pass. Sufficiently together means enough together so that the insect does not pass but not too close together to prevent the porosity is too low. According to this approach (the efficacy depends on the warp threads), the weft threads are separated to reduce the surface area occupied by the solid matrix and thus to increase the porosity values. This gives as a result holes of rectangular geometry where the ratio between the width and length ($L_{sc,w}/L_{sc,l}$) are usually smaller than 0.5 (Table 1). If this ratio is very low means that the hole is very elongated and the insect can have gap to cross between the central axis (dashed line in Figure 5) and the weft threads that delimits the hole (since the warp threads are progressively separated in the perpendicular plane to the fabric).

In Figure 6 are represented the hole surfaces of the physical barriers studied versus its efficacy against *B. tabaci*. The points associated with very low efficacies correspond with physical barriers that allow crossing practically all the insects. However, it can be seen that as the efficiency increases the trend lines of screens and perforated sheets intersect. This is because in the case of screens part of the porous surface is not useful (because the holes are very elongated) for the passage of the insect and for this reason the results obtained with the two groups of physical barriers are no comparable.

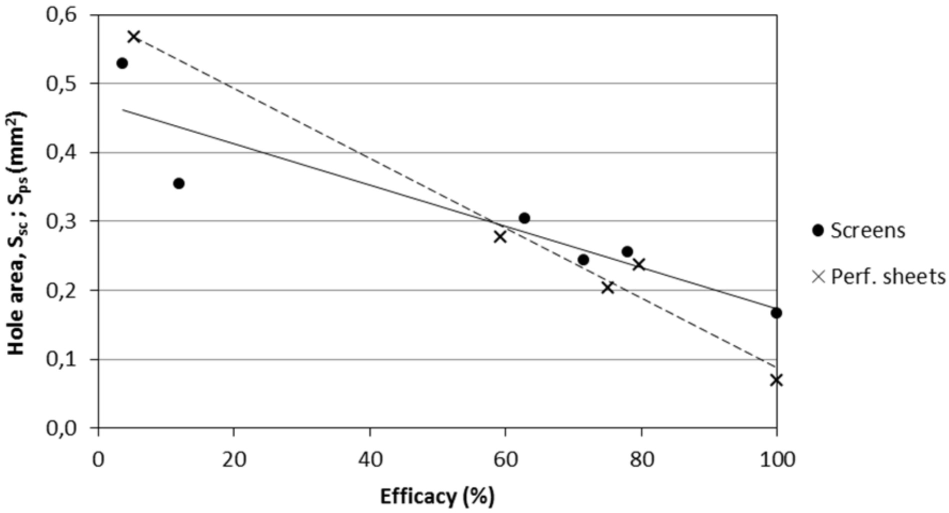

Figure 6. Relationship between the hole surface area (S_{sc} and S_{ps}) and the screen efficacy.

CONCLUSIONS

Since its appearance, the design of screens is an aspect that has barely evolved. In general, the design criteria considered is to reduce the separation between the warp threads (prison effect) to prevent the entry of insects and increase the separation of the weft threads to improve the porosity of the textile. The data reveal that the separation of the weft threads must also be taken account in assessing the efficacy of the insect exclusion screens given the spatial arrangement of the warp threads. The most critical hole region for the passage of the insect is the distance defined by the crossing of two consecutive warp threads (dashed line in Figure 5). It can be said that this separation divides the hole in two parts useful for insect passage. Therefore, the insect cannot cross if this separation is less than its body size. In spite of this, if the hole is very elongated the insect could pass by one of the halves, since the warp threads are separated in the orthogonal plane of the textile leaving a porous surface larger of which can be measured in orthogonal projection.

The geometry and the shape factor of the holes of the screens and perforated sheets must be similar to indirectly obtain a measure of the 3D surface of the holes of the screens by comparison with the surface of the perforated sheets (2D). Hole widths smaller than the minor axes of the holes of the perforated sheets are required to achieve a given value of efficacy due to the spatial arrangement of the threads.

This work is valid to *B. tabaci*. Insects with other features need a particular study to draw conclusions that allow improving the design of the insect-proof screens.

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