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Textile Physical Barriers against the Chestnut Gall Wasp *Dryocosmus kuriphilus*

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Abstract: *Dryocosmus kuriphilus* Yasumatsu is a species originating from China that, during the 20th century, has spread rapidly throughout many countries, affecting mainly different species of the genus *Castanea* spp. In fact, it is considered to be the most important pest of chestnut trees (*Castanea sativa* Miller), causing significant production losses. The adoption of complementary measures to chemical and biological controls would contribute to the control of the pest. In this sense, the use of textile physical barriers could prevent the rapid spread of this species among the production centers. Therefore, the objective of this study is to define the characteristics of a textile that protects young plants that have been produced in nurseries. For this purpose, some commercial textiles have been selected based on the morphometric characterization of the species and these textiles have been accurately measured in order to compare their dimensions with those of the insects. Finally, tests have been carried out in order to measure the efficacy of the textiles under laboratory conditions, controlling the air velocity and the temperature. The results reveal that, in general, theoretical efficacy may not be a good predictor of practical results. A fully effective screen has been found against this species and its design characteristics can be used as a starting point for new, more optimized designs.

Keywords: physical barriers; insect-proof screens; *Dryocosmus kuriphilus*; gall wasp; *Castanea*

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1. Introduction

Dryocosmus kuriphilus Yasumatsu (Hymenoptera: Cynipidae) is a species that is native to China, which is commonly known as the chestnut gall wasp. It was first described in Europe (Italy, southern Piedmont) in 2002 [1]. It is considered to be a pest that exclusively attacks the trees of the genus *Castanea*. It causes significant yield reductions [2], a reduction in the leaf area and, therefore, of photosynthetic capacity [3], decay, and even the death of the tree in cases of severe infestations [4,5]. In Spain, it was detected for the first time in Catalonia in 2012 [6] and during the following years it has spread rapidly throughout the main production areas.

The life cycle of this species is univoltine, which is closely related to temperature. In summer, the females (there are only females) oviposit inside buds. During the followings months, the larvae develop, resulting in the formation of green or pinks galls in the final period of their development. The galls provide food for the progeny and protection against abiotic factors and against natural enemies, as the young remain hidden inside of the tissues where they feed and develop [7]. Early detection is not possible until the development is well advanced in the following spring. The adults emerge from the end of May to the end of July.

The rapid spread of this species is mainly due to the movement of infested plant material from nurseries to production sites [8–10]. Since neither chemical control methods based on authorized materials nor biological controls (results can be seen after several years [11]) have been shown to be effective to combat this species or to prevent its spread, preventive measures stand as the most appropriate in order to stop the rapid expansion of *D. kuriphilus*.

Protective textiles are a method of pest control whose use has spread rapidly in many regions of the world [12–17] due to good results that have been obtained with different pests (whiteflies, aphids, thrips, miner flies, etc.,); although no previous study has been carried out with *D. kuriphilus*. Non-woven fabrics are found within the group of protective textiles (although their main application is different), but insect proof screens are more widespread and more widely used. The structure of the woven screens is determined by two sets of threads (weft and warp) that interweave perpendicularly. The separation between the threads and the thickness of the threads define the size of the holes. The design of the protective screens is a very complex matter, and the best approach can be addressed from different points of view that very often offer opposing solutions (exclusion vs. ventilation and light transmission) [12,18,19]. Protective screens reduce the populations of pests in the crop environment [20–22] and decrease the incidence of insect-borne diseases [23–26] and, as a result, the need for pesticide application is reduced [13,22,23,27,28]. In addition, some studies have shown promising results regarding the incorporation of insecticides into the threads making up the textile [29,30] and recently, some works have been carried out on the addition of different types of silica (SiO_2) nanoparticles as a non-toxic substance for insect control [31,32].

During the vegetative rest (from December to March) most chestnut trees are marketed. In this period the plant is asymptomatic, and its phytosanitary status cannot be guaranteed by the naked eye. Therefore, in order to protect the plant material that is produced in nurseries and to avoid the movement of plants from infected areas to healthy areas, this work aims to evaluate the effectiveness of different insect-proof screens against *D. kuriphilus*, since the textile physical barriers could be a preventive solution against infestations in nurseries and thus the spread of the pest by this route. Finally, a completely effective screen against *D. kuriphilus* has been found.

2. Materials and Methods

2.1. Infested Plant Material

The individuals used in the trials came from the *Centro de Investigación Forestal de Lourizán* (Pontevedra, Spain). Two shipments of branches that were infested by *D. kuriphilus* were sent to the Laboratory of Agrotextiles of the University of Almeria from two sites, As Neves Pontevedra→42°8′14″/8°24′17″ and Lugo→42°59′49″. In each shipment, six polystyrene boxes were received with a total of 15–20 branches per box (Figure 1).

Figure 1. Receipt of the first shipment of infested chestnut branches.

To prevent the dehydration of the plant material, each branch was placed in a Falcon tube with water. Branches with galls were isolated in cages that were covered with a non-woven polypropylene fabric (Figure 1). These structures prevented the adults from escaping after emerging and facilitated their capture with the help of an entomological aspirator. The Falcon tubes were filled daily with water using a pipette. The plant material remained in a good condition for around three weeks.

2.2. Morphometric Analysis of D. kuriphilus

The selection of insect-proof screens as a physical method of protection against a specific pest requires the geometric characterization of the textiles and the morphometric study of the pest. The morphological measurements of the different individuals were carried out on digital images that were obtained under a stereomicroscope incorporating a digital camera and Motic Images Plus 2.0 software. Initially, the microscope was calibrated in order to obtain the equivalent metric units of each pixel.

To facilitate the manipulation of the wasps, the insects that were captured in the cages were placed in a Petri dish and then anesthetized with a few drops of chloroform. The anesthetized insects were then arranged in groups of ten individuals on a slide to capture the images. On these images, the length, the thorax and abdomen width (dorsal view (x-axis), and a lateral view (z-axis)) were measured for each of the analyzed insects (Figure 2).

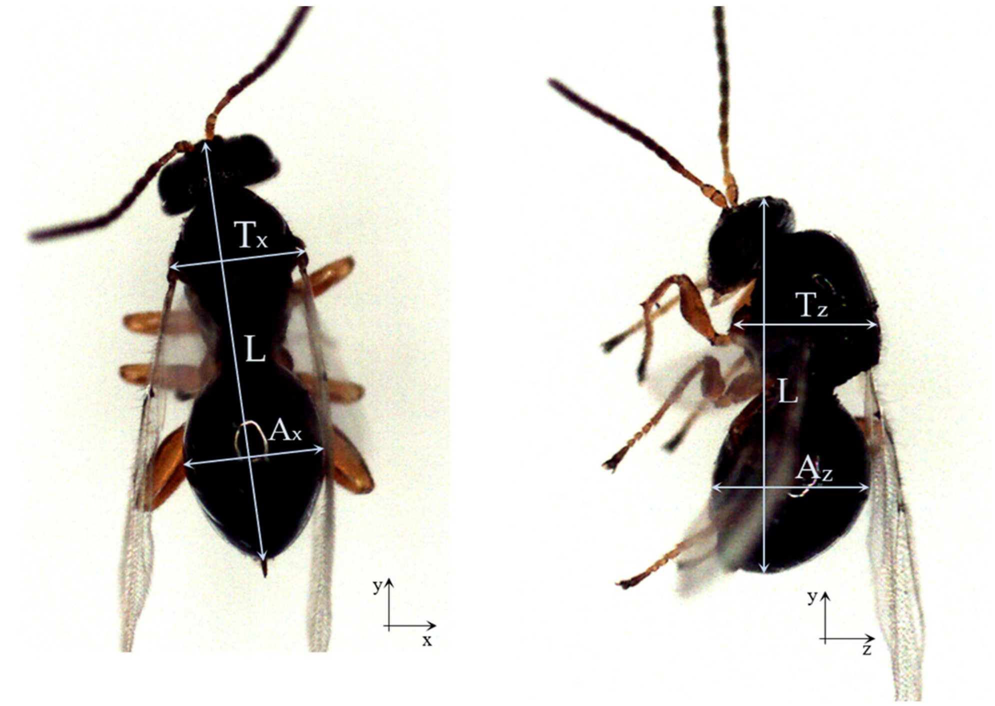

Figure 2. Individual of *D. kuriphilus* (dorsal view (**left**), lateral view (**right**)).

2.3. Geometric Characterization of the Selected Textiles

The measurement of the hole size of the protection textiles was performed on digital images using the software Euclides v.1.4 [33,34]. The digital images (Figure 3) were taken using a Motic DMWB1–223 microscope with an Altra 20 digital camera (Olympus). The calibration of the microscope allowed the evaluation of the equivalent metric units of each pixel. A total of 800 holes per textile were measured. It was necessary to take different image captures of each textile to cover the number of holes since the scanning field was too small, even when using the lowest magnification objective (4×), and only a few holes could be obtained per image, depending on the density of the threads in the sample. The precision of the measurements obtained on the microscopic images corresponded to one pixel and the calibration performed with the microscope for the objective used in the image capture (4×) established a ratio of 8.297 μm pixel^{-1}. Euclides v.1.4 requires black and white images, in which the white pixels correspond to the holes of the textile and the black pixels correspond to the threads (Figure 3). The measurements were based on obtaining the vertices that were defined by the crossing between the threads that made up the screen. The software scanned the image by rows of pixels and was able to identify these vertices. After some corrections, Euclides v.1.4 read the coordinates of these vertices and related them to the hole to which they belonged. With these data, all the geometrical characteristics of the protection screens could be obtained by applying Euclidean geometry. The Euclides v.1.4 software calculated the following geometrical parameters: the number of threads per unit length (density of threads) in the weft and warp directions, the thickness of the threads, the dimensions and surface area of the holes, the textile porosity, and the diameter of the largest circumference inscribed in the holes.

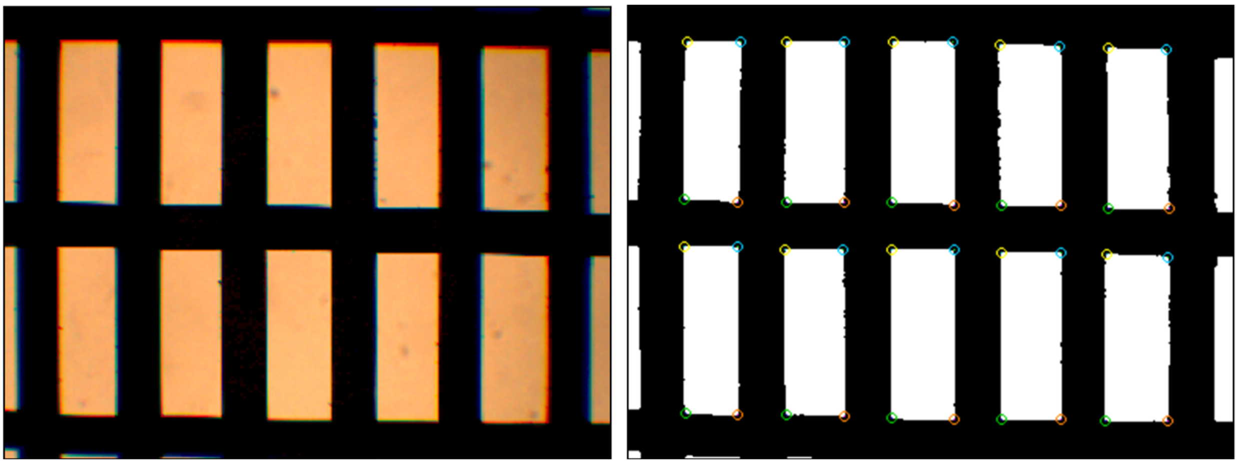

Figure 3. Microscopic image (**left**); same image analyzed by Euclides v.1.4 (**right**).

All the above-mentioned parameters describe the screen from the point of view of its orthogonal projection. However, from a microscopic point of view, the spatial arrangement of the threads that make up the textile suggests that this 2D approach is not sufficient to explain the relationship between the screen and the insect. The real surface area that defines the three-dimensional space between the threads is a region of the hyperbolic paraboloid [35], as can be seen in Figure 4. Using the variables that describe the protection screen from the 2D perspective (length L_{py} and width L_{px} of the hole and thickness of the warp thread D_{hy}), and considering the thickness of the textile t_t measured using a micrometer (model 3050T, Baxlo) according to the standard ISO 5084: 1996 [36], the surface area of the screen measured in 3D can be calculated using the method proposed by [35] as follows:

$$A_{3D} = \frac{a^4}{3}\left[F(1) - F\left(\frac{-c+ad}{c}\right) + G\left(\frac{ad}{2c-ad}\right) - G(0) - \frac{\pi}{2}\right] \quad (1)$$

where a, c, and d are geometric parameters (Figure 4) and $F()$, and $G()$ are functions that depend on these parameters:

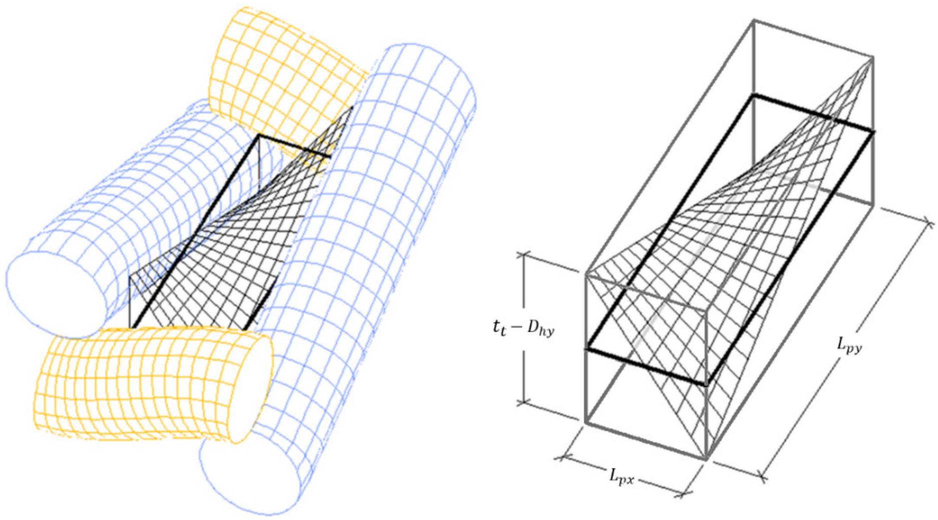

Figure 4. Three-dimensional representation of a hole and 3D surface area; definition of the parameters *a*, *c*, and *d*.

The parameters *a*, *c*, and *d* are as follows:

$$a = \sqrt{\frac{L_{px}L_{py}}{t_t - D_{hy}}} \tag{2}$$

$$c = \frac{L_{px} + L_{py}}{2\sqrt{2}} \tag{3}$$

$$d = \sqrt{\frac{L_{px}\left(t_t - D_{hy}\right)}{2L_{py}}} \tag{4}$$

and the functions $F()$ and $G()$ are as follows:

$$F(1) = \frac{\pi}{2} - \frac{d\left(3a^2 + 2d^2\right)}{a^3\sqrt{2}} \ln\left(d\sqrt{2a^2 + 4d^2}\right) \tag{5}$$

$$\begin{aligned} F(t) = {} & \frac{d^2(t-1)\sqrt{a^2(t+1)^2+4d^2(t^2+1)}}{a^3(t+1)^2} - \tan^{-1}\left(\frac{\sqrt{a^2(t+1)^2+4d^2(t^2+1)}}{a(t-1)}\right) \\ & -\frac{d\left(3a^2+2d^2\right)}{a^3\sqrt{2}} \ln\left(\frac{-2d^2(t-1)+d\sqrt{2}\sqrt{a^2(t+1)^2+4d^2}\left(t^2+1\right)}{t+1}\right) \end{aligned} \tag{6}$$

where t is a geometric variable that, when it comes to assessing the function $F(t)$, is $(-c + ad)/c$.

$$\begin{aligned} G(t) = {} & \frac{(2c-ad)^2}{a^6} t\sqrt{a^4 + 2(2c - ad)^2(t^2 + 1)} + \tan^{-1}\left(\frac{a^2 t}{\sqrt{a^4+2(2c-ad)^2(t^2+1)}}\right) \\ & + \frac{(2c-ad)\left(3a^4+2(2c-ad)^2\right)}{a^6\sqrt{2}} \ln\left(2(2c - ad)t + \sqrt{2a^4 + 4(2c - ad)^2(t^2 + 1)}\right) \end{aligned} \tag{7}$$

where t is a geometric variable that, when it comes to assessing the function $G(t)$, is $(ad)/(2c - ad)$.

Another parameter that becomes interesting when considering the 3D structure of the textile is the distance d_2 that is a generatrix of the 3D hole surface and it is defined as the average spatial separation between the warp threads, considering the middle of the hole from the point of view of its length (Figure 5). Theoretically, the hole width L_{px} measured in 2D prevents the entry of the insects if the dimension is smaller than the insect's body size. However, the hole width L_{px} does not change when the hole length L_{py} increases (this happens when the distance between the weft threads increases) or when the thickness of the screen varies and, although the 2D surface area increases, it is not relevant from an insect exclusion point of view. However, when the hole length L_{py} increases the spatial separation of the warp threads (z-axis) it leaves a gap (3D) through which insects can cross the textile if the gap is big enough. A way to measure this gap and to theoretically know if the insect can pass through the hole is by the 3D surface area A_{3D} and the generatrix d_2. This distance can be calculated using the following method proposed by [35]:

$$d_2 = \sqrt{L_{px}^2 + \left(\frac{t_t - \mathrm{D}_{hy}}{2}\right)^2} \tag{8}$$

where L_{px} is the hole width measured in orthogonal projection, D_{hy} is the thickness of the warp threads (usually the thickness of the weft and warp threads is the same), and t_t is the screen thickness.

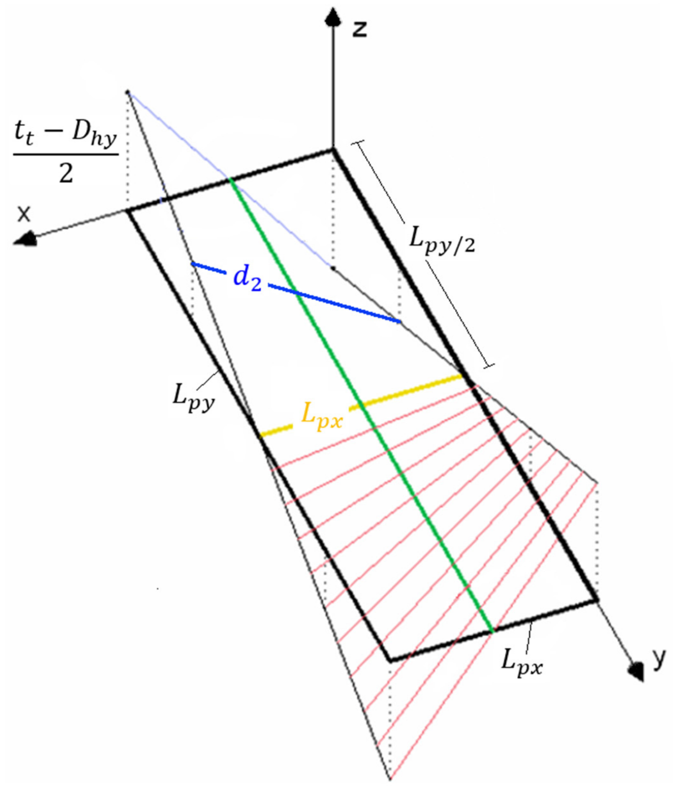

Figure 5. Graphic definition of the generatrix d_2.

2.4. Theoretical Efficacy of the Textiles against D. kuriphilus

The determination of the theoretical efficacy of the screens consists of a comparison between the mean hole dimensions and the mean values of the thorax width of the species to be excluded. Typically, the thorax size is chosen because this tagma is the most rigid [37].

For a textile to be effective against a given pest, the separation between the warp threads must be less than the size of the thorax measured on the insect's cross section. However, as noted above, the problem is much more complex, since in an insect population there are individuals of different sizes and there are even important differences between the sizes of male and female individuals (although this is not the case here since all individuals are female). Therefore, the use of mean values is simply a selection criterion and it is clear that, due to the heterogeneity of sizes within populations, it would be more appropriate to choose, instead of mean values, values corresponding to, for example, the 90th of 95th percentile. The heterogeneity of the hole sizes of the textile is an additional problem, and for this reason it is necessary to certify the uniformity of the hole dimensions of the marketed textiles. Therefore, due to the complexity of taking into account the nonmeasurable variables, such as the ability of the insect to pass through the holes, the screens need to be subjected to laboratory tests where the efficiency of the screen is measured against the studied species.

In addition, the spatial arrangement of the threads suggests that the passage surface for the insects is greater than that measured in the orthogonal projection images. In addition, air velocity and temperature are variables that influence the efficacy of these textiles and, therefore, it is necessary to contrast the theoretical effectiveness with the results obtained in tests carried out by confronting the textile with the insects.

2.5. Efficacy of the Screens against *D. kuriphilus* Measured under Laboratory Conditions

The efficacy of insect-proof screens against *D. kuriphilus* was determined under laboratory conditions. For this purpose, an experimental device was used to obtain the exclusion capacity of the agrotextiles both in calm conditions and at different air velocities (Figure 6).

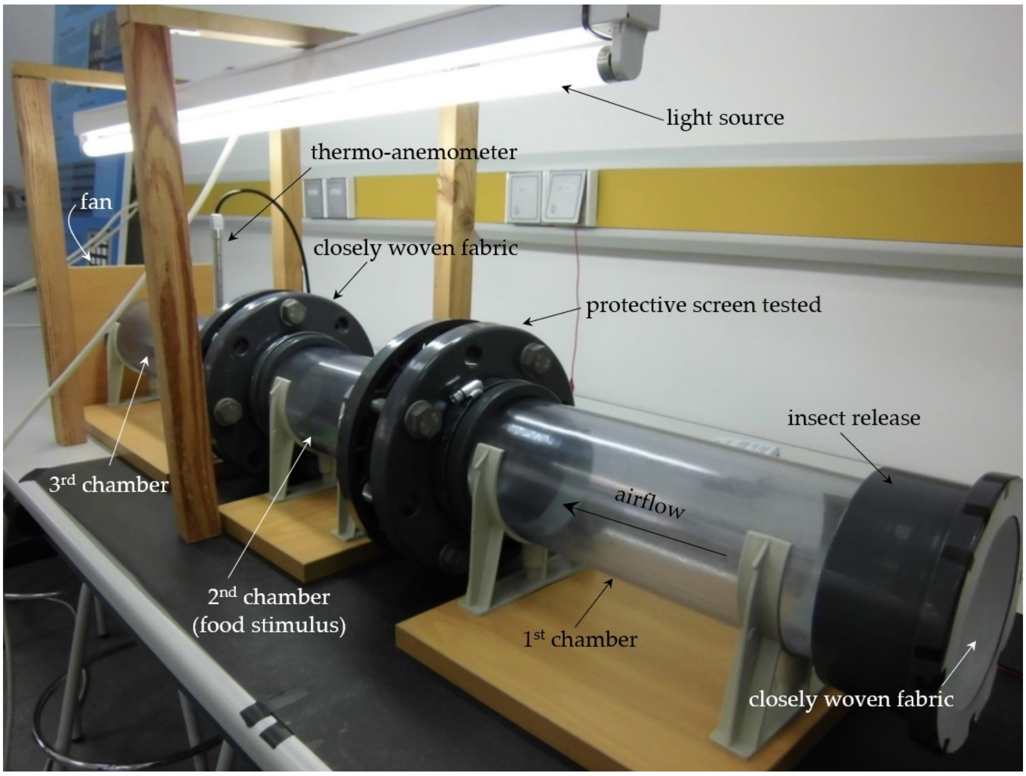

Figure 6. Experimental device for measuring the protective efficacy of screens.

A transparent PVC tube with a diameter of 11 cm was divided into three compartments of chambers. The union between the first and second compartments was achieved by means of a set of flanges between which the textile sample to be analyzed was inserted (Figure 6). The third chamber was joined to the second compartment by another flanged joint, in which a very dense fabric was placed to allow air flow but prevent the passage of insects from the second chamber to the third compartment. A hot wire thermo-anemometer (model HD29V37TC12, Delta OHM, Selvazzano Dentro, Italy) was placed in the third chamber to measure the temperature and air velocity, in addition, a DC fan was placed in this chamber. This fan allowed us to establish an air flow inside the device. The experimental set-up was managed by the Bóreas v.1.3 software that allowed the test variables to be set and the air velocity (which was constant in each test) and temperature to be recorded.

During the tests, the insects were introduced into the first compartment through a small hole. This compartment was covered with a black plastic film to prevent the passage of light. The second chamber was illuminated with a fluorescent tube (Philips TL-D 36W/54–765) so that the light acted as a visual attraction and, therefore, motivated the insects to pass through the textile by moving from the first chamber to the illuminated chamber. In addition to the light stimulus, a food stimulus (chestnut leaves) was introduced into the illuminated chamber.

The duration of each test was 24 h. After this time, the insects were anaesthetized with an overdose of chloroform to facilitate handling. Finally, the number of insects in the first and second chambers were counted. To obtain statistical validity, three repetitions of each test were carried out. With these values, the exclusion coefficient to the tested textiles was determined. The efficacy ε of a protection screen was calculated using the following expression:

$$\varepsilon\ (\%) = \frac{N_{1c}}{N_{1C} + N_{2C}}\, 100 \tag{9}$$

where N_{1C} is the number of insects trapped in the first chamber and N_{2C} is the number of insects that crossed through the holes of the screen (second chamber).

3. Results and Discussion

3.1. Dimensions of *D. kuriphilus*

The dimensions of the thorax and abdomen of *D. kuriphilus* are shown in Table 1. A total of 165 individuals were analyzed, differentiating between the individuals that emerged from the first shipment of the infested plant material (As Neves Pontevedra: 42°8′14″/8°24′17) and those that emerged from the second shipment (Lugo: 42°59′49″/7°32′47″). The results obtained show no significant differences between the sizes of the individuals from these two areas of origin.

Table 1. Determination of the mean size of the thorax (T), in dorsal (x), and lateral (z) view and of the abdomen (A), in dorsal (x), and lateral (z) view of the sample of n adults that emerged in the laboratory.

Origin	n	$T_x \pm \sigma$ (µm)	$T_z \pm \sigma$ (µm)	$A_x \pm \sigma$ (µm)	$A_z \pm \sigma$ (µm)
As Neves Pontevedra 42°8′14″/8°24′17″	82	732 ± 39	745 ± 37	773 ± 38	854 ± 28
Lugo 42°59′49″/7°32′47″	83	717 ± 44	736 ± 48	762 ± 49	859 ± 94
Mean values	165	725 ± 42	741 ± 43	768 ± 45	857 ± 69

The mean size of the abdomen width in lateral view (A_z = 857 µm) is larger (89 µm) than that in dorsal view (A_x = 768 µm). The differences between the mean sizes of the thorax width that were measured in dorsal (T_x = 725 µm) and lateral (T_z = 741 µm) views are smaller (16 µm). When there are differences between the dorsal and lateral views, the textiles with square-hole geometry are more suitable than the textiles with rectangular-hole geometry. The reason for this statement is that the insect species with transverse asymmetry of their body find a way of entry through the rectangular holes by orienting their most limiting dimension in the direction of the hole length (similar to inserting a coin through a slot).

The thorax is the most limiting dimension for insects when crossing a textile, according to [37], despite the fact that this tagma is smaller than the abdomen. However, the thorax is more rigid and for this reason it is taken as the reference measurement, so the selected screens should have a hole width that is lower than the dimensions of the wasp thorax. From a theoretical point of view, in protective screens with rectangular-hole geometry, the hole width should be smaller than the smallest average value of the selected tagma (T_x = 725 µm) in order to prevent the insects from crossing the screen by taking advantage of the hole length. However, in textiles with square-hole geometry (less common on the market), the diagonal dimension should be smaller than the largest average value of the selected tagma (T_z = 741 µm).

3.2. Geometry of Protection Screens

Considering the average body dimensions of *D. kuriphilus*, five commercial screens were chosen whose hole widths were 82 μm above (L_{px} = 807 μm = 725 μm + 82 μm→screen five) and 86 μm below (L_{px} = 639 μm = 725 μm − 86 μm→screen two) the selected reference value (T_x = 725 μm). According to the measurement procedure that is described in Section 2, the geometrical parameters that were obtained for these five textiles are shown in Table 2.

Table 2. Results of geometrical analyses: mean density of threads in warp ρ_y and weft ρ_x directions; mean hole width L_{px}; mean hole length L_{py}; mean thread thickness D_h; porosity φ.

Screen	$\rho_y \times \rho_x$ Trade Values (Threads cm^{-2})	$\rho_y \times \rho_x$ Measured Values (Threads cm^{-2})	$L_{px} \pm \sigma$ (μm)	$L_{py} \pm \sigma$ (μm)	$D_h \pm \sigma$ (μm)	φ (%)
1	10 × 7	10.5 × 7.3	669 ± 19	1082 ± 33	281 ± 14	56.0
2	10 × 8	10.6 × 8.1	639 ± 36	930 ± 35	300 ± 13	51.5
3	10 × 10	10.0 × 9.6	715 ± 25	742 ± 30	295 ± 17	50.6
4	9 × 6	9.4 × 6.6	748 ± 72	1221 ± 25	310 ± 18	56.2
5	9 × 6	8.9 × 6.2	807 ± 36	1298 ± 50	316 ± 18	57.9

As can be seen in Table 2, the selected screens present rectangular-hole geometry and, in all cases, the porosity values are above 50%. Only screen three shows smaller differences between the hole length and width, so it can be said that it has a "squarer" hole geometry. The thicknesses of the threads that were used were around 300 μm. The rectangular-hole geometries followed a design strategy known as the "prison effect", which aims, with unequal importance depending on the target species, to improve the porosity of the textiles and/or reduce the manufacturing cost by eliminating the weft threads. In this case, the porosities are high and the resistance to airflow that was caused by the screens (in order to allow ventilation of the plant environment) does not limit their use. It is also true that the porosities could be much higher if the textiles were made with thinner threads.

The values that characterize the screens from a 3D point of view (Table 3) have been calculated from the data shown in Table 2 and the textile thickness t_t has been measured as indicated in Section 2. A shape factor (L_{px}/L_{py}) has also been calculated that values the ratio between the width and the length of the holes in such a way that the values close to unity correspond to the holes with a geometry close to square. Table 3 includes the surface area of the holes A_{2D} that were measured in 2D (L_{px} L_{py}) in order to be able to compare with the real average surface area A_{3D} of the holes that were calculated according to Equation (1).

Table 3. Shape factor L_{px}/L_{py}; textile thickness t_t; surface area of the holes measured in orthogonal projection A_{2D}, real surface area A_{3D}; length of the generatrix d_2 and half of the hole length $L_{py/2}$.

Screen	L_{px}/L_{py}	$t_t \pm \sigma$ (μm)	A_{2D} (mm^2)	A_{3D} (mm^2)	d_2 (μm)	$L_{py/2}$ (μm)
1	0.62	510 ± 5	0.7239	0.7430	679	541
2	0.69	530 ± 4	0.5943	0.6127	649	465
3	0.96	460 ± 9	0.5305	0.5395	720	371
4	0.61	560 ± 7	0.9133	0.9363	758	611
5	0.62	530 ± 7	1.0475	1.0643	814	649

Screens one, two, four, and five have shape factors between 0.61 and 0.69. Only screen three differs from the previous ones with a shape factor higher than 0.95. This textile is also the only screen with a thickness t_t lower than 500 μm, which suggests that there are smaller differences between the parameters that were measured in orthogonal projections (on the images) and those that were calculated for the three dimensions.

3.3. Efficacy of Protection Screens

Table 3 shows the efficacy values of the five textiles that were tested against *D. kuriphilus* at different values of air velocity (0, 1.5, and 3.0 m·s^{-1}). Moreover, together with the efficacy values, the average temperatures at which each test was carried out are shown (these are the average temperatures of the three repetitions that were carried out) due to the influence that this variable has on the activity of the insects and, therefore, on the efficacy of the textiles. Expressing the results in this way allows the efficacies obtained in this work to be compared with future experiments.

Screens four and five are the textiles with the largest hole sizes (Tables 3 and 4) and, accordingly, the ones with the worst efficacy values against *D. kuriphilus* under calm conditions, 76.4% and 76.3%, respectively. For these textiles, the average real surface area of the holes A_{3D} was above 0.93 mm^2 and the shape factor was not greater than 0.62. Given the size of the insect (not too small compared to other species, such as *Bemisia tabaci* or *Frankliniella occidentalis*) and the damage it causes, the aim here was to find fully effective protective screens against this pest. For this reason, and due to the small size of the insect sample we had, it was decided not to carry out the tests with these screens at air velocities of 1.5 and 3.0 m s^{-1}. In any case, and according to our experience, the effect of the wind will cause the efficacy of these textiles, which are partially effective at 0 m s^{-1}, to be reduced as the air velocity increases [38].

Table 4. Efficacy results of the textiles against *D. kuriphilus* in the tests carried out at 0, 1.5, and 3.0 m s^{-1} and the statistics according to a one-way ANOVA test ($p \leq 0.05$).

Screen	ε (%); *T* (°C)			F-Value	*p*-Value
	0 m·s^{-1}	1.5 m·s^{-1}	3.0 m·s^{-1}		
1	98.4; 28.9	100; 28.4	100; 28.4	1.000	0.422
2	98.1; 29.2	93.8; 28.5	94.8; 29.7	0.357	0.714
3	100; 28.6	100; 28.4	100; 29.6	—	—
4	76.4; 28.6	—	—	—	
5	64.3; 28.7	—	—	—	

Next, the results that were obtained for screens one and two showed efficacies above 90%. The shape factors of these screens were 0.62 and 0.69, respectively. The 3D surface area of their holes was within the range of 0.60–0.75 mm^2. The results that were obtained for these two screens were inconsistent in the sense that screen two, which had a smaller hole size, should have achieved higher efficacies than screen one, and not the other way around. It is difficult to explain these differences, but they may be due to the small number of individuals that were available in each repetition (around 17 individuals) and the heterogeneity of sizes between the individuals that were used in the trials. The effect of the air velocity (in order to simulate the wind), which tends to reduce the efficacy of protective textiles, is not clearly seen in these results, probably for the reasons that have been mentioned above or because the hole size was small enough and, therefore, the air velocity does not influence the efficacy of the textile. The statistical analysis that was performed (one-way ANOVA test [39]) does not show statistically significant differences in the textile efficacy according to the air velocity (Table 4).

Screen three was completely effective under the conditions that were set out in the tests. This textile occupies an intermediate position in terms of average hole width L_{px} since there are textiles with the smaller hole widths that have allowed some insects to pass through. However, this screen had the smallest hole length L_{py}, which determined that the shape factor was 0.96 and this value is notably different from the rest of the selected screens. The real hole surface area was less than 0.54 mm^2. This hole width would let the wasps pass through the screen if the hole length was larger, as with screens one and two, because the insects crossed the screen through one of the hole halves, although this cannot be said considering only the 2D parameters and an explanation must be found in the 3D arrangement of the threads. Therefore, a hole width (2D) lower than the insect reference dimension (T_x = 725) is not a guarantee that the screen will be effective. The same could be said about the generatrix d_2. However, screen three had the lowest 3D surface area A_{3D}, so the combination of this variable, along with the generatrix d_2, suggests that this screen is a completely effective protective barrier (at least against the conditions tested here). These two parameters consider the hole width L_{px} and length L_{py} and the thickness t_t of the screen. However, the insect's ability is also an important factor in insect exclusion [37].

This study adds to other works that have assessed the efficacy of protective screens against other pests. Except for the case of *F. occidentalis* [38], these studies reveal promising results against the main insect pests. Therefore, the use of protective screens should be an additional and essential measure in Integrated Pest Management (IPM) [40–42]. Furthermore, the incorporation of additives into the threads [29,32,43] opens up a new range of possibilities, such as the use of less dense screens to prevent small insects without the drawback of the airflow resistance that current textiles offer.

This work paves the way for future research, but some aspects can be improved. For example, a greater number of wasps would be desirable to carry out the tests. On the other hand, although 3 $m{\cdot}s^{-1}$ is not a very high air velocity, we have observed that as this variable increases, the insects tend not to move and they will seek protection from the wind; for this reason, it would be advisable to introduce wind gusts in the tests that are carried out at higher air velocities. For example, a planned test at 5 $m{\cdot}s^{-1}$ would be carried out at this maximum air velocity, alternated with "short periods" of lower velocities. A new work could also assess how to improve the simulation of the wind in the laboratory. In addition, of course, new works could optimize the design of a completely effective screen against *D. kuriphilus*.

4. Conclusions

A completely effective textile has been found to protect chestnut trees that are produced in nurseries against *D. kuriphilus* and to avoid their spread by preventing the infested plant material from travelling to areas that are free of this pest. The holes with rectangular geometry and with hole widths that were smaller than the thorax width of this wasp measured in dorsal view have allowed the entry of smaller individuals due to the spatial arrangement of the threads, which suggests that the passage surface area is larger than the surface area that was measured in orthogonal projection. The only textile with "square" hole geometry that was evaluated in the trials gave better results (fully effective) than the rectangular geometries even though, in some cases, the latter screens had smaller hole width sizes L_{px}. Therefore, the design criterion (prison effect) based on restricting the hole width in order to prevent insect passage and increasing the length in order to avoid reductions in porosity does not give good results for this pest, at least in the range of geometric values of the screens tested here.

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