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Analysis of the effects of shading screens on the microclimate of greenhouses and glass facade buildings

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1 Analysis of the shading screen effects on greenhouse  
2 environmental conditions evaluated with CFD  
3 simulations

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10 **Abstract**

11 Shading devices are widely used in the protected crop cultivation, mostly in the  
12 Mediterranean area, since they allow to reduce the strong solar radiation effects in  
13 the closed environment. On the contrary, they have negative effects on the ven-  
14 tilation efficiency of the greenhouse especially if they have low porous texture and  
15 therefore they represent an obstacle to passage of air. Moreover, investigations about  
16 indoor environmental conditions and distributions can allow to improve the manage-  
17 ment of indoor climate, by means of the optimization of greenhouse structure and  
18 air conditioning systems. This requires the characterization and the modeling of the  
19 processes involved, and in particular of the convective heat transfer. In recent years,  
20 Computational Fluid Dynamics (CFD) methods have been employed to investigate  
21 scalar and vector variables which determines greenhouse microclimate with respect  
22 to its structural specifications and equipment. So far, the majority of studies, re-  
23 lated to the effects of shade screens on greenhouse climate, focused on experimental  
24 investigation based on analytic model. Only few studies have used CFD simulations  
25 to explore the response of greenhouse climate factors to the change of shading pa-  
26 rameters. The present study aims to investigate, by means of a CFD approach, the  
27 distribution of temperature and air flow in a naturally ventilated three-span glass  
28 greenhouse, taking into consideration the external incident radiation, the optical  
29 properties of the materials and the presence of shading devices inside the structure.

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30 *Keywords:* Natural Ventilation, Solar radiation, CFD Modeling,  
31 Greenhouse, Shading screens

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32 **1. Introduction**

33 The Computational Fluid Dynamics (CFD) analyses are nowadays a pow-  
34 erful tool for modeling air flows and climate patterns in agricultural struc-  
35 tures, like greenhouses. The CFD allows to investigate the influence of the

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36 greenhouse design parameters, wind direction, location of the mechanical ven-  
37 tilation devices, on different microclimatic parameters like temperature and  
38 humidity distributions, ventilation flow rate and incident solar radiation (Roy  
39 and Boulard, 2005). The use of CFD has been consolidated as a method for  
40 predicting also the climate conditions of inner crops by resolving the equations  
41 of heat and mass transfer for an accurate mesh of discrete locations (Boulard  
42 et al., 2002).

43 In Mediterranean countries, a concerning aspect for the crop growth is the in-  
44 door climate management during the hot and sunny days usually characterized  
45 by high-intensity solar radiation (He et al., 2014). The climate management is  
46 a fundamental aspect for a productive greenhouse since it influences not only  
47 the growth of crops, but also the energy needs of the facility (Barbaresi et al.,  
48 2020) and then the profitability and sustainability of the sector. Several meth-  
49 ods can be used for cooling the greenhouse environment in order to establish  
50 more suitable conditions for crop growth. Natural ventilation is usually the  
51 first option due to its low cost and simplicity, but it can be insufficient for  
52 controlling heat gain and high temperature peaks during sunny summer days  
53 (Baille, 1999). Then, other cooling methods have to be considered in combi-  
54 nation with natural ventilation (Katsoulas et al., 2001). A solution used more  
55 and more is the introduction of shade screens, which could be placed inter-  
56 nally or externally to the cladding, to attenuate the incoming solar radiation  
57 and to avoid the direct damage of the intense sunshine to the crop's growth  
58 during hot days (He et al., 2014). In fact, shading can be accomplished in  
59 different ways. A popular technique consists in placing a porous screen over  
60 the cover, adhering to it, or fixed atop the greenhouse, letting the outside air  
61 flow beneath the screen and above the greenhouse (Piscia et al., 2012). These  
62 devices have been investigated under several aspects by the researchers. The  
63 first aspect of interest concerns the evaluation of the effects of the modifica-  
64 tion of some shading parameters (e.g. shade combination, rate and level) on  
65 the air temperature, climate heterogeneity, spectral distribution and growth  
66 of the crops inside the greenhouse (Montero et al., 2013; Piscia et al., 2012;  
67 Kitta et al., 2012; Kittas et al., 2003; Sapounas et al., 2010). On the other  
68 hand, the interest has been focused on the physical properties of the shading  
69 materials (Santolini et al., 2019; Miguel et al., 1997; Miguel, 1998; Miguel and  
70 Silva, 2000; Valera et al., 2006, 2005) and their impact on greenhouse climate  
71 (Santolini et al., 2018; Baxevanou et al., 2010; Kittas et al., 1999).

72 Considering the relevant role of the solar radiation for the plant growth, in-  
73 formation about quantity, quality and spatial distribution of daylight trans-  
74 mitted by greenhouse cladding and shading materials is essential to assess  
75 their influence on growth and development of crops (Baxevanou et al., 2010;  
76 Santolini et al., 2020; Barbaresi et al., 2020). The climate distribution pre-  
77 dictions could allow to save energy and reduce the use of pests, enabling pest  
78 and disease control in a more sustainable way. Moreover, information about  
79 indoor environmental conditions and distributions should help to improve cli-  
80 mate homogeneity, obtained by the optimization of both greenhouse structure

81 and climate air conditioning systems. This requires the characterization and  
82 the modeling of the processes involved, such as convective heat transfer mecha-  
83 nism (Boulard et al., 2002). In recent years, few studies used CFD methods to  
84 investigate scalar and vector parameters of the greenhouse microclimate with  
85 respect to structural characteristics and conditioning systems (Boulard et al.,  
86 2002; Bartzanas et al., 2004; Fatnassi et al., 2006; Santolini et al., 2018). So  
87 far, most studies related to the effect of shading screens on greenhouse climate  
88 focused on experimental investigations or by adopting analytic models. Few  
89 researchers employed numerical methods, e.g. CFD, to explore the response  
90 of greenhouse climate by changing the shading parameters. Therefore, the ap-  
91 plication of CFD approach to investigate the greenhouse microclimate pattern  
92 and the shading performances, in different configurations and for the local cli-  
93 mate condition, actually is a promising but almost unexplored research field  
94 (He et al., 2014).

95 In the present study, a CFD model has been used to investigate the distribu-  
96 tions of both temperature and air flow in a naturally ventilated three-span glass  
97 greenhouse, also taking into account the incident solar radiation. The radiative  
98 properties of the materials of the envelope and the presence of shading devices  
99 have been properly taken into account. In particular, the paper analyses the  
100 effects of three shading devices on the indoor conditions of a greenhouse. The  
101 three shading devices have similar radiative properties but different textures.  
102 Four different environmental scenarios, simulating four different conditions of  
103 summer days in the Mediterranean areas, have been analyzed and compared.  
104 The study brings together a novel CFD approach and a new method for climate  
105 indoor measurements. The novel CFD approach consists in coupling a CFD  
106 modeling of radiation and the approach for the simulation of the presence of  
107 screens for screens Santolini et al. (2019). The innovative approach for indoor  
108 experimental measurements is a patented technique that, by means of acoustic  
109 measurements, allows to reach a very accurate determination of the position  
110 of the sensors. The innovative method, described and proposed in the present  
111 paper, provides very accurate evaluations of the shading effect of the different  
112 screens in the analyzed scenarios. This approach allows to increase the knowl-  
113 edge of the screens behavior in protected crop cultivation and provides useful  
114 indications about their application in this sector.

## 115 **2. Materials and Methods**

116 The research has been developed by means of both experimental tests and  
117 numerical models carried out on a case study. It is a three-span greenhouse of  
118 the University of Bologna, sited in Imola, Italy (about 30 km East of Bologna).  
119 The different spans are separated by glass walls and are connected through in-  
120 ternal doors. The investigations have been focused on the SE span, highlighted  
121 in blue, visible in Fig. 1. This span is provided with three benches for exper-  
122 imental crop cultivation has an independent control unit for indoor climate  
123 control, managing heating and cooling systems, vent opening, and shading

124 curtains.

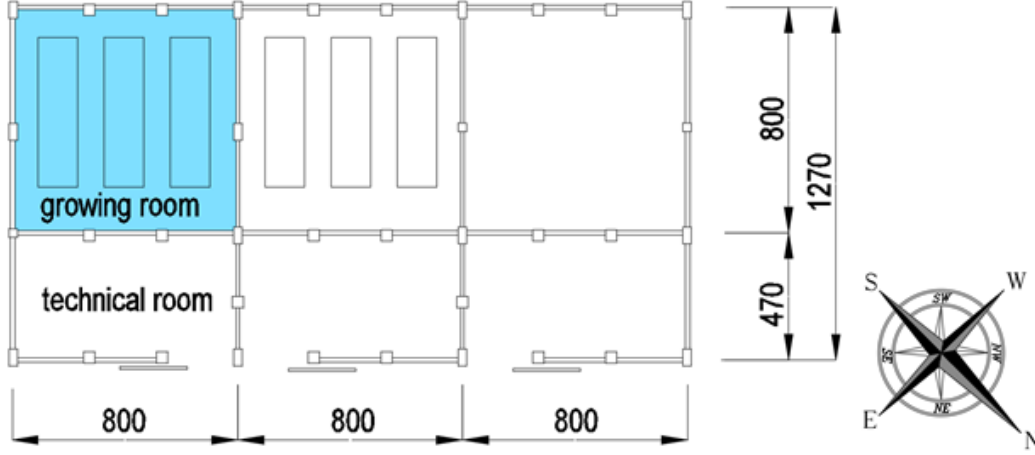


Figure 1: Section in plan of the greenhouse under study.

125 The volume of the span is divided, by means of a wall, in two different  
 126 portions (see Figure 1). The main area is devoted to the cultivation of crops  
 127 whereas the smaller area is a technical room hosting the heating and cooling  
 128 systems. The outcomes of the investigations presented here considers only the  
 129 main area of the span. The numerical simulations have been carried out with  
 130 Ansys-Fluent 17.2 code (Fluent Inc, 2006). The computational domain is a  
 131 parallelepiped with dimensions, in horizontal plane, 244.0 m x 63.5 m and 27.5  
 132 m in the vertical direction.

### 133 2.1. Numerical model description

134 The flow inside the greenhouse is considered unsteady, incompressible and  
 135 turbulent. The flow and the transport phenomena for air flow and the heat  
 136 transfer, are described by the Navier-Stokes equations. The time-averaged  
 137 Navier-Stokes equations, for the mass, momentum and energy transport are  
 138 presented in the following equations (1)(2) (Baxevanou et al., 2010):

$$\frac{\Delta U_i}{\Delta x_i} = 0 \quad (1)$$

$$\rho U_j \frac{\delta U_i}{\delta x_j} = -\frac{\Delta P}{\Delta x_i} + \frac{\delta}{\delta x_j} [(\mu + \mu_t) \frac{\delta U_i}{\delta x_j}] + f_b + S_j \quad (2)$$

139 where  $U$  is the fluid velocity,  $P$  is the fluid pressure,  $\rho$  is the fluid density,  $\mu$   
 140 is the fluid dynamic viscosity,  $\mu_t$  is the turbulent viscosity,  $S_j$  is a source term  
 141 and  $f_b$  is a vector which represents the body forces. The density variation was  
 142 calculated according to the Boussinesq model in order to take into account  
 143 the natural convection effects. The turbulence effects on the flow have been  
 144 implemented in the Re-Normalization Group (RNG) based on  $k-\varepsilon$  model. The  
 145 standard  $k-\varepsilon$  model is a semi-empirical model (see 3 and 4), based on model

146 transport equations for the turbulent kinetic energy ( $k$ ) and its dissipation rate  
 147 ( $\varepsilon$ ) (Yakhot et al., 1992).

$$\frac{\delta}{\delta t}(\rho k) + \frac{\delta}{\delta x_i}(\rho k u_i) = \frac{\delta}{\delta x_j}[(\mu + \frac{\mu_t}{\sigma_k}) \frac{\delta k}{\delta x_j}] + G_b + G_k - \rho \varepsilon - Y_M + S_k \quad (3)$$

$$\frac{\delta}{\delta t}(\rho \varepsilon) + \frac{\delta}{\delta x_i}(\rho \varepsilon u_i) = \frac{\delta}{\delta x_j}[(\mu + \frac{\mu_t}{\sigma_\varepsilon}) \frac{\delta \varepsilon}{\delta x_j}] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (4)$$

148 The RNG approach, which is a mathematical technique that can be used  
 149 to derive a turbulence model similar to the standard  $k$ - $\varepsilon$  model, results in a  
 150 modified form of the epsilon equation which attempts to account for the dif-  
 151 ferent scales of motion through changes to the generation term. In particular,  
 152 the RNG model considers these refinements, visible from the comparison of 3  
 153 and 4 with 5 and 6:

$$\frac{\delta}{\delta t}(\rho \varepsilon) + \frac{\delta}{\delta x_i}(\rho \varepsilon u_i) = \frac{\delta}{\delta x_j}[(\alpha_k \mu_{eff}) \frac{\delta \varepsilon}{\delta x_j}] + G_b + G_k - \rho \varepsilon - Y_M + S_k \quad (5)$$

$$\frac{\delta}{\delta t}(\rho \varepsilon) + \frac{\delta}{\delta x_i}(\rho \varepsilon u_i) = \frac{\delta}{\delta x_j}[(\alpha_\varepsilon \mu_{eff}) \frac{\delta \varepsilon}{\delta x_j}] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \quad (6)$$

- 154 • The RNG model has an additional term in the  $\varepsilon$  equation that signifi-  
 155 cantly improves the accuracy for rapidly strained flows;
- 156 • The effect of swirl on turbulence is included in the RNG model, enhancing  
 157 accuracy for swirling flows;
- 158 • While the standard  $k$ - $\varepsilon$  model is a high-Reynolds-number model, the  
 159 RNG theory provides an analytically-derived differential formula for ef-  
 160 fective viscosity that accounts for low-Reynolds-number effects. Effective  
 161 use of this feature, however, depends on an appropriate treatment of the  
 162 near-wall region.

163 These features make the RNG  $k$ - $\varepsilon$  model more accurate and reliable for a  
 164 wider class of turbulent flows. The complete set of the equations can be found  
 165 in Lien and Leschziner (1994). The Semi-Implicit Method for Pressure-Linked  
 166 Equations (SIMPLE) algorithm has been used to take into account pressure-  
 167 velocity coupling and second-order discretization schemes have been used for  
 168 convective and viscous terms of the governing equations. The velocity has  
 169 been monitored in some particular points of the model in order to assess the  
 170 on-grid convergence of the solution. The convergence criteria have been set

171 equal to  $10^{-5}$  for the scaled residuals of each variables.  
172 For this study, where the radiation plays a significant role, the Discrete Ordi-  
173 nates Radiation model(DO model) has been used. The model considers both  
174 the solar radiation and the radiations between the greenhouse surfaces. The  
175 DO model allows to reach the solution in those applications facing with radia-  
176 tion on semi-transparent walls and can be applied to both gray and non-gray  
177 radiation by a gray-band model. The model considers the absorption coeffi-  
178 cients of the surfaces since they can vary within spectral bands (Raithby, 1999;  
179 Baxevanou et al., 2010). The DO model solves the general radiation transfer  
180 equation (RTE) for a set of  $n$  different directions for a finite number of discrete  
181 solid angles, each one associated with a fixed vector direction. The angles  $\theta$   
182 and  $\phi$  are the polar and azimuthal angles and they are constants.  
183 In the simulations, these angles have been divided in four control angle for  $\theta$   
184 and  $\phi$  (Piscia et al., 2012; Raithby, 1999; Murthy and Mathur, 2008). The ra-  
185 diation equations were computed every 10 iterations. Baxevanou et al. (2008)  
186 described in details the DO model applied to CFD models of greenhouses. In  
187 the model, the specific thermal-radiative characteristics of the materials of the  
188 greenhouse have been defined, as reported in Tables 1 and 2.

Table 1: Thermal characteristics of the materials, used as initial conditions.

Material	Density ( $\rho$ ) ( $\text{kg m}^{-3}$ )	Conductivity ( $\kappa$ ) ( $\text{W m}^{-1}\text{K}^{-1}$ )	Specific heat capacity ( $C_p$ ) ( $\text{J kg}^{-1}\text{K}^{-1}$ )
Glass	2530	1.2	840
Aluminum	2719	202.4	871
Soil	1620	1.3	1480
Concrete	2200	1.5	1000

Table 2: Radiative characteristics of the materials, used as initial conditions.

Material	Absorbance	Emissivity
Glass	0.7	0.9
Aluminium	0.2	0.5
Soil	0.9	0.925
Concrete	0.6	0.88

189 The walls have been modeled as semi-transparent surfaces of tempered  
190 glass 4 mm thick, the benches have aluminum structures and surfaces, and the  
191 pavement has been considered a concrete slab.  
192 Considering the greenhouse is naturally ventilated, a logarithmic wind profile  
193 has been set at the inlet of the domain,

$$u_{wind} = \frac{u_*}{\kappa} \log\left(\frac{z + z_0}{z_0}\right) \quad (7)$$



194 from which depends the turbulent kinetic energy ( $k$ ) and the dissipation  
 195 rate ( $\varepsilon$ ):

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \quad (8)$$

$$\varepsilon = \frac{u_*^3}{\kappa(z + z_0)} \quad (9)$$

196 where  $u_*$  is the friction wind speed,  $z$  is the elevation calculated starting  
 197 from the ground level,  $z_0$  is the surface roughness,  $\kappa$  is the von Karman's con-  
 198 stant assumed equal to 0.40 and  $C_\mu$  is a experimental constant. The shading  
 199 devices have been modeled by means of the porous-jump model, based on  
 200 the Darcy-Forchheimer law which relates the pressure drop of the fluid flow  
 201 through a porous medium with its physical characteristics (Santolini et al.,  
 202 2019). Each one of the three screens has been defined by assuming its phys-  
 203 ical and radiative properties, as reported in Table 3 and obtained from the  
 204 experimental tests described in Santolini et al. (2019).

Table 3: Physical and radiative properties of shading devices adopted in the present work.

Screen	Thickness (mm)	Permeability (1/m)	Inertial coefficient (1/m <sup>2</sup> )	<i>Shading<sub>dir</sub></i> (%)	<i>Shading<sub>diff</sub></i> (%)
H3647	0.36	1.4883	$7.2080 \times 10^{-11}$	43	50
H4215	0.32	0.5794	$2.6627 \times 10^{-09}$	48	53
H5220	0.32	0.2759	$4.9085 \times 10^{-10}$	52	52

205 These screens properties (see Tab.3) depend on the specific grid texture  
 206 which could affect the air distribution, by means of permeability and inertial  
 207 coefficient. In fact, the texture is characterized by a sequence of permeable  
 208 layers, made of a weft of plastic thread, and impermeable layers, made of plastic  
 209 strips. The number and sequence of these two types of strips determines the  
 210 interaction of the screen with the incoming air flow.

## 211 2.2. *Experimental campaign*

### 212 2.2.1. *Data acquisition*

213 An experimental campaign has been conducted during a sunny day (23/04/2018),  
 214 collecting data of direct solar radiation, indoor air velocity and temperature.  
 215 The boundary conditions of the CFD simulations have been defined based on  
 216 these measurements.

217 The solar radiation has been measured by a pyranometer (Delta Ohm with  
 218 accuracy of 10 V/(W/m<sup>2</sup>)), positioned in the proximity of the greenhouse. The  
 219 averaged direct solar radiation has been calculated as:

$$\frac{1}{n} \sum_{i=0}^n (x_i) \quad (10)$$



Figure 2: Description of the case study greenhouse: (a) Plan view of the building; (b) Inner view of the productive surface; (c) Images of the system used for locating the measurements (yellow circle).

220 where:  $x_i$  are the single data and  $n$  is the number of measurements. The  
 221 magnitude and vector components of wind velocity have been collected by a  
 222 weather station placed *in situ*. The indoor air velocity and temperature have  
 223 been measured with a hot-wire anemometer (Delta Ohm with accuracy of 0.01  
 224 m/s). Each velocity measurement is the average of about 60 data collected in  
 225 a time period of 2 seconds.

### 226 2.2.2. Positioning system description

227 An innovative 3D patented positioning system has been used to define in a  
 228 precise way the position of the sensors. The system (Guidorzi, Jun 14, 2017)  
 229 is shown in Fig. 2 (see the yellow circle). It is based on acoustic measurements  
 230 and is similar, in principle, to the global positioning system (GPS). The com-  
 231 ponents of the system are: a 1 m x 1 m grid with 4 amplified loudspeakers (A,  
 232 B, C and D in Fig. 3a)), a small microphone, a multi-channel sound card and a  
 233 computer, running a software created ad-hoc, that manages the measurements  
 234 and records the acquired data.

235 The microphone, whose position is to be determined, receives the sounds  
 236 emitted by the four loudspeakers on the grid. From the four arrival times  
 237 of the respective acoustic waves and knowing the speed of sound in the air  
 238 (as a function of the temperature), the 4 distances from the microphone and  
 239 the loudspeakers are measured. To better understand why it is necessary to  
 240 measure 4 distances, the problem of determining the position of a point on a 2D  
 241 plane is considered as example, with reference to Fig. 3b), if only the distance  
 242 of the unknown position target (yellow point) from a known position point 1  
 243 is available, the possible solutions are represented by the black circumference;  
 244 if the distances of the target from two known position points, 1 and 2, are  
 245 available, two solutions (intersections of the black and blue circumferences)  
 246 are possible. Finally, if the distances from three known position points, 1, 2  
 247 and 3, are available, a single solution, intersection of the three circumferences,

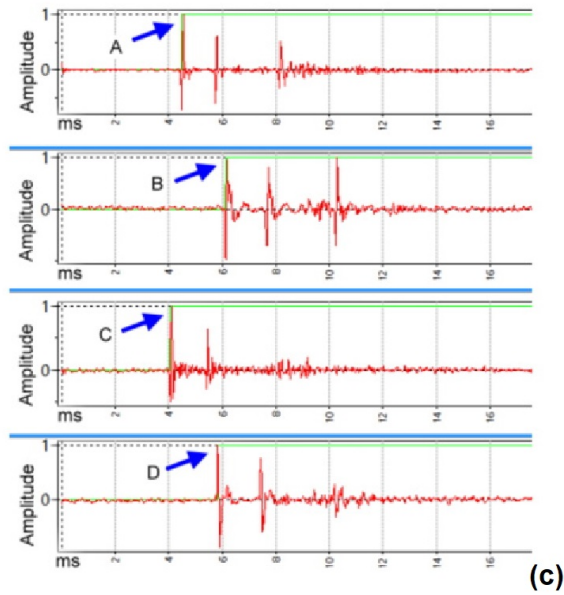
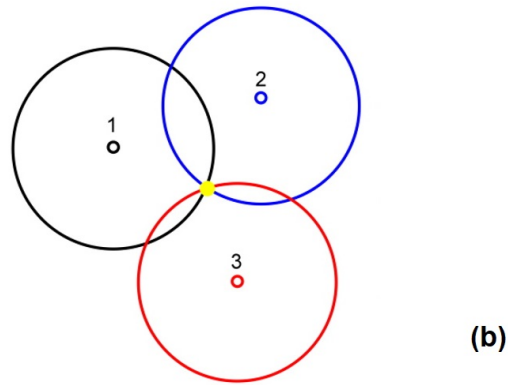
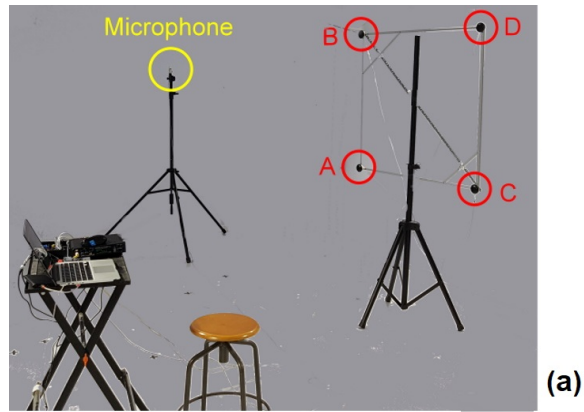


Figure 3: a) Geometrical setup of the 3D positioning system; b) Trilateration on a two-dimensional plane; c) Example of impulse responses acquired by the four loudspeakers.

248 is found. Extending the reasoning to the 3D space, knowing the distance of  
 249 the target point from a point of known position, the possible solutions are on a  
 250 sphere centered in the known position; if the distances from two known points

251 are available, the possible solutions are on the circumference intersection of the  
 252 two spheres centered in the known points; if the distances from three known  
 253 points are available, two possible solutions exist. Finally if the distances from  
 254 four known points are available, only one solution is obtained and it is the  
 255 exact position of the target in the 3D space. The intersection point of the four  
 256 spheres can be found by solving the following system:

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = r_1^2 \quad (11a)$$

257

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = r_2^2 \quad (11b)$$

258

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = r_3^2 \quad (11c)$$

259

$$(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 = r_4^2 \quad (11d)$$

260 where:

- 261 • the microphone (target) in the unknown position is at the coordinates  
 262  $(x, y, z)$ ;
- 263 • the centers of the four spheres (i.e. the positions of the four loudspeakers)  
 264 are in the known positions with coordinates  $(x_1, y_1, z_1)$ ,  $(x_2, y_2, z_2)$ ,  $(x_3,$   
 265  $y_3, z_3)$  and  $(x_4, y_4, z_4)$ ;
- 266 • the distances between the four loudspeakers and the target, i.e. the rays  
 267 of the four spheres, are respectively  $r_1, r_2, r_3$  and  $r_4$ .

268 The solution of the system of eq.11a, 11b, 11c and 11d) is explained in  
 269 detail in the Appendix.

270 The measurement of the four distances between the grid and the microphone is  
 271 carried out by simultaneously emitting from the four loudspeakers, four MLS  
 272 (Maximum Length Sequence) pseudo-random audio signals. MLS signals have  
 273 an audio spectrum similar to the white noise and are commonly used in the field  
 274 of the acoustic such as the test of noise barriers (Garai et al., 2014; Garai and  
 275 Guidorzi, 2015). The loudspeakers emit different MLS signals, with the same  
 276 time length and orthogonal to each other. Thanks to the properties of the MLS  
 277 sequences (Borish and Angell, 1983; Rife and Vanderkooy, 1989; Vanderkooy,  
 278 1994), it is possible to distinguish the four different signals at the microphone  
 279 even if they are emitted simultaneously. Using the Fast Hadamard Transform  
 280 (FHT) algorithm, four different impulse responses are obtained from the audio  
 281 signals sampled by the microphone, as shown in Fig.3 (c). From the timing of  
 282 the first peak on the responses, it is possible to measure the arrival time of the  
 283 sound from the four loudspeakers to the microphone. The generic distance,  $s$ ,  
 284 traveled by a sound wave in air between a loudspeaker and the microphone is  
 285 calculated with the formula:

$$s = t \cdot c \quad (m) \quad (12)$$

286 where  $t$  is the flight time (in seconds) determined by the first peak of  
 287 the impulse response, as described above, and  $c$  is the speed of sound in air  
 288 depending on the temperature according to the formula:

$$c = 331.6 + 0.6 \cdot T \quad (m/s) \quad (13)$$

289 where  $T$  is the air temperature ( $^{\circ}C$ ).

290 MLS signals are immune to background noise, and then measurements can be  
 291 made in noisy environments also. A necessary condition for the application of  
 292 the methodology is that the loudspeakers must be in sight of the microphone,  
 293 in order to avoid the 4 loudspeakers must be properly placed so do not have  
 294 inter-visibility problem. Small obstacles, (e.g. thin branches and leaves) are  
 295 not a problem and have not created issues during the tests in the greenhouse.

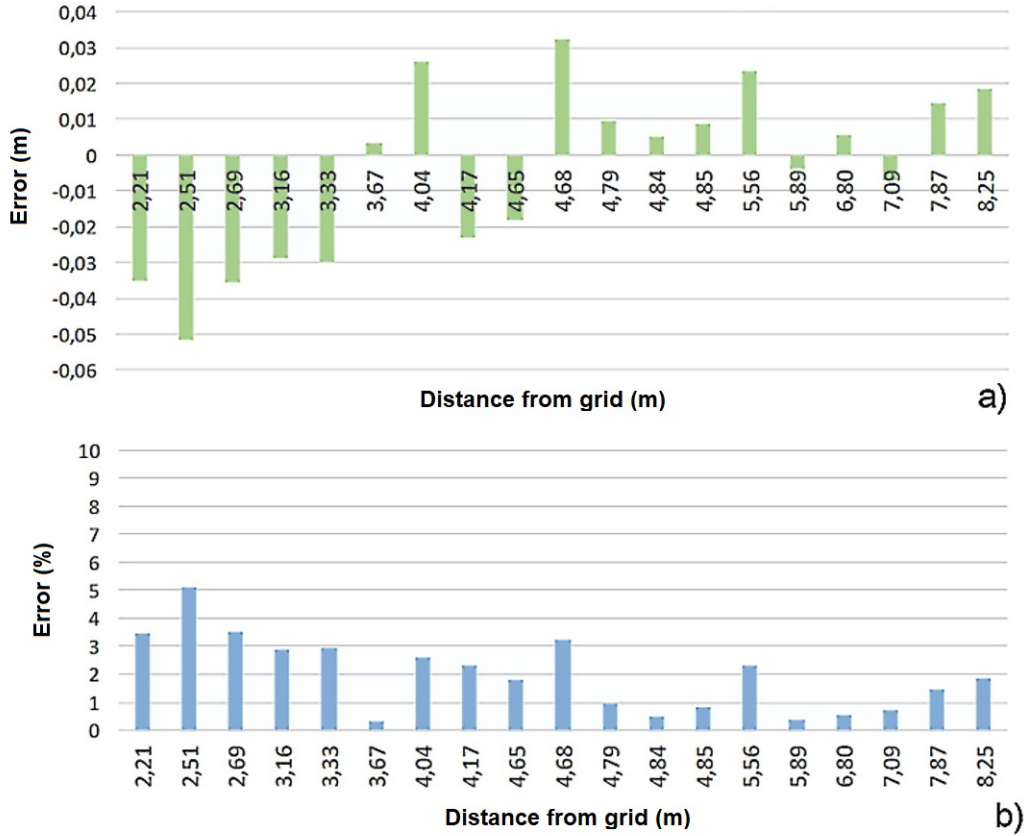


Figure 4: **a)** Measurement error on 1 m distance (sample rate 96 kHz); **b)** Percentage of error on distance measurements in a).

296 The accuracy of the measurement system depends on many factors, includ-  
 297 ing the geometry of the measurement grid, the sampling rate of the sound card  
 298 and the distance of the microphone from the grid. In particular, the sampling

299 rate determines the time step of the measured data and therefore the mini-  
 300 mum distance distinguishable from the peaks of the impulse responses: with  
 301 a 44.1 kHz sampling rate, the time step is 0.0104161667 ms, corresponding to  
 302 a distance of about 7.8 mm, at a sound speed of 343 m/s; at 96 kHz sampling  
 303 rate, the resolution on the distance is about 3.6 mm. However, an evaluation  
 304 of the real accuracy of the system is not simple because the data of the indi-  
 305 vidual distances are processed by the trilateration algorithm (searching for the  
 306 solution of the system of Equations 11a, 11b, 11c and 11d). In order to have  
 307 an assessment of the percentage error on the 3D position detected, a series of  
 308 measurements, allowing a statistical analysis, were carried out, measuring the  
 309 exact length of 1 meter at different distances from the loudspeaker grid, with  
 310 various combinations of sampling rates. It has been found that, employing a  
 311 1 m x 1 m grid, the detection system works correctly inside an area of about  
 312 10 m in each spatial direction, starting from the grid. Probably, by increasing  
 313 the size of the grid, it should be possible to extend this range. At a sample  
 314 rate of 96 kHz, as can be seen in Figure 4 a), for the positions at least 3 meters  
 315 away from the grid, the absolute error is generally less than 3 cm. The average  
 316 error, over all distances, is less than 2%, with a standard deviation of 2.34 cm.  
 317 The accuracy of the positioning system therefore can be considered suitable  
 318 for the type of measurements, realized in the present work.

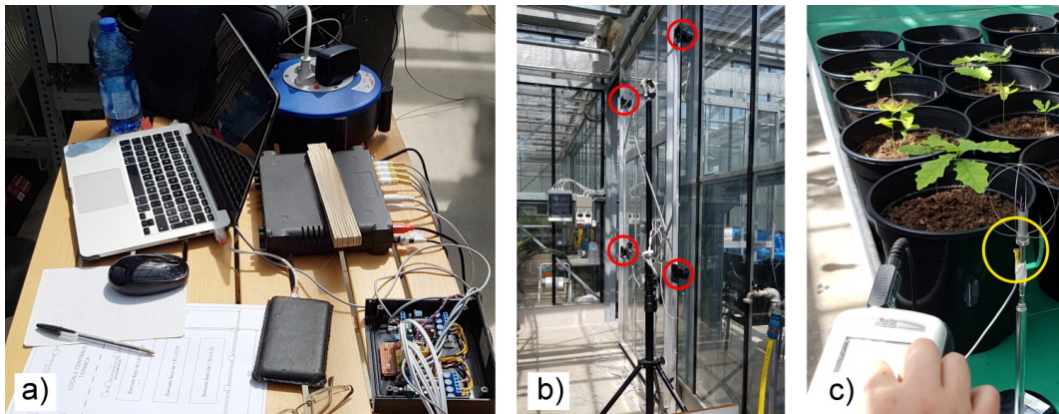


Figure 5: (a) Measurement system (computer, soundcard, amplifiers); (b) grid with loudspeakers; (c) particular of the microphone attached to the thermal probe.

319 Figure 5 shows the components of the positioning system: Fig 5 a) depicts  
 320 the computer with the software that generates the MLS signals, samples the  
 321 signal from the microphone, performs the trilateration calculations and saves  
 322 the data. In Fig.5 a) the sound card and the electronic cards with the amplifiers  
 323 for the loudspeakers are also visible. In Fig.5 b), the grid with the loudspeakers  
 324 is shown. In Fig.5 c) the microphone attached to the anemometer is shown.  
 325 The fixed distance between the microphone and the thermal sensor has been  
 326 taken into account in the assessment of the positions.



327 *2.3. Numerical model validation*

328 Twenty four locations have been defined in the cultivation area, at three  
329 different levels, e.g. 1.0 m , 1.7 m and 3.0 m.

330 The numerical model of the case study has been validated against the col-  
331 lected experimental data. In the first simulation, the average of the solar  
332 radiation and wind velocity values collected during the whole experimental  
333 campaign, have been set as boundary conditions. The diffuse solar radiation  
334 value has been estimated by the solar calculator included in Ansys Fluent,  
335 on the basis of the geographical coordinates of the site, day and hour of the  
336 beginning of the measurements (23/04/2018, 11:30 am, local time). The di-  
337 rect solar radiation data shows a significant variation during the period of the  
338 experimental campaign, as showed in Figure 6. In fact, Figure 6 shows vari-  
339 ation values, even higher than  $300 \text{ W/m}^2$  in one hour. The solar radiation  
340 can significantly affect the indoor airflow distribution in a naturally ventilated  
341 greenhouse and then an approach adopting the average value could be too  
342 simplified.

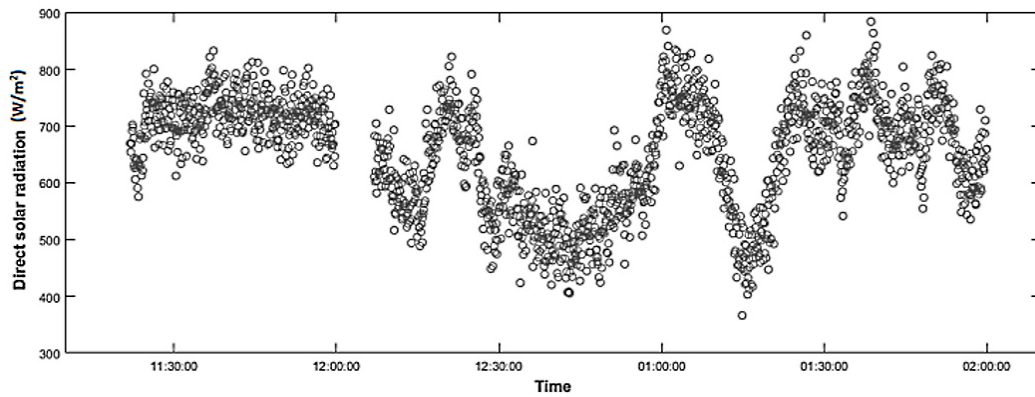


Figure 6: Direct solar radiation recorded by the pyranometer located in the proximity of the greenhouse.

343 Then, the direct solar radiation, averaged in a period of 15 minutes, has  
344 been used in the simulations. Figure 7 shows the comparison between the  
345 velocity values measured in the greenhouse and those obtained by the CFD  
346 simulation for the twenty four different positions.

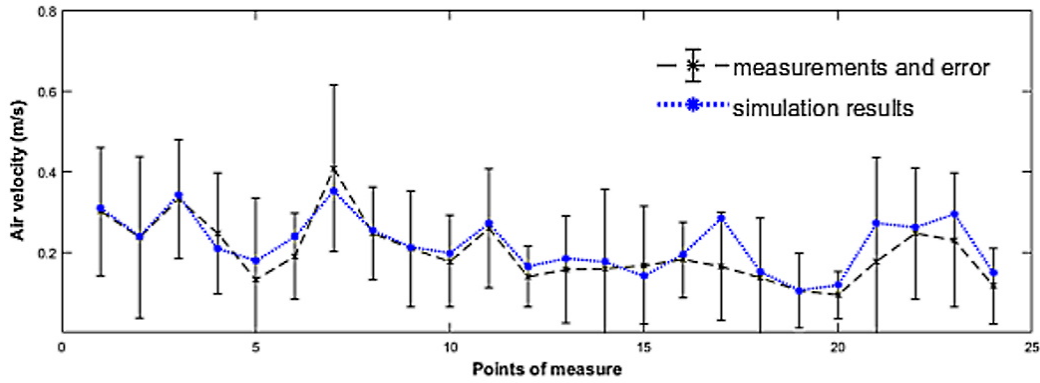


Figure 7: Comparison between measured air velocities and CFD simulation results.

347 The Figure 7 shows a very good agreement between the numerical results  
 348 and the experimental measurements, with very low value of root mean square  
 349 error (RMSE) that, calculated on the total set of measurements, results equal  
 350 to 0.14 m/s.

#### 351 *2.4. Scenarios and combinations investigated*

352 The solar radiation could significantly affect the indoor microclimate con-  
 353 ditions of a greenhouse during the sunny days, especially in Mediterranean  
 354 climate. Moreover, as showed before, the solar radiation can vary considerably  
 355 from hour to hour, the radiation value assumed in the simulation can strongly  
 356 influence the numerical results. Then, in order to have results representative  
 357 of the typical conditions of the site during the hot season, the weather data  
 358 collected during the whole summer season 2017 have been considered. Two  
 359 representative conditions have been chosen. The first condition considers a  
 360 strong direct solar radiation with low wind velocity. The second assumes a  
 361 moderate direct solar radiation with high wind velocity. The first condition  
 362 corresponds to peaks of solar radiation intensity, while the second intends to  
 363 evaluate the typical trend of the indoor parameters during the summer season.  
 364 Each condition has been analyzed by assuming two different representative  
 365 wind directions, i.e. North-West and South-East, providing four representa-  
 366 tive ventilation scenarios for the structure at hand.

367 The cases have been performed considering the implementation of three dif-  
 368 ferent shading screens with different geometrical and radiation characteristics,  
 369 (see Santolini et al. (2019)). The shading screens are placed inside the cultiva-  
 370 tion area in three different positions: one is horizontally located at about 4.0  
 371 m height; one is laterally placed close to the lateral vent and one is located  
 372 in the back of the room, close to the back wall (see Fig. 8). The three differ-  
 373 ent screens are characterized by different texture (variations of porosity and  
 374 inertial coefficient) but they have similar radiative properties.

375 The effects of the presence of the screens have been investigated in terms  
 376 of both entering solar radiation and ventilation efficiency. The sixteen combi-  
 377 nations of inlet velocity and solar radiation, summarized in Table 4, have been



Table 4: Summary of the 16 combinations investigated in this work:  $T_{initial}$  is the defined initial temperature, IR is the initial direct solar radiation value and  $v_{friction}$  is the friction velocity considered for the wind profile definition.

Scenario	$T_{initial}$ ( $^{\circ}\text{C}$ )	IR ( $\text{W}/\text{m}^2$ )	$v_{friction}$ (m/s)	Wind direction	Screen	Combinations
1	22.8	794.5	6.3	NW	No screen	1
					H3467	2
					H4215	3
					H5220	4
2	22.8	794.5	6.3	SE	No screen	5
					H3467	6
					H4215	7
					H5220	8
3	30.8	1030	2	NW	No screen	9
					H3467	10
					H4215	11
					H5220	12
4	30.8	1030	2	SE	No screen	13
					H3467	14
					H4215	15
					H5220	16

378 obtained by crossing four scenarios and four shading assumptions (i.e. the no  
379 screens condition and three different screens). The wind directions North-West  
380 (NW) and South-East (SE) in Table 4 has been obtained from the statistical  
381 analysis of the wind data available for 2017. They represent the direction more  
382 representative for the summer season.

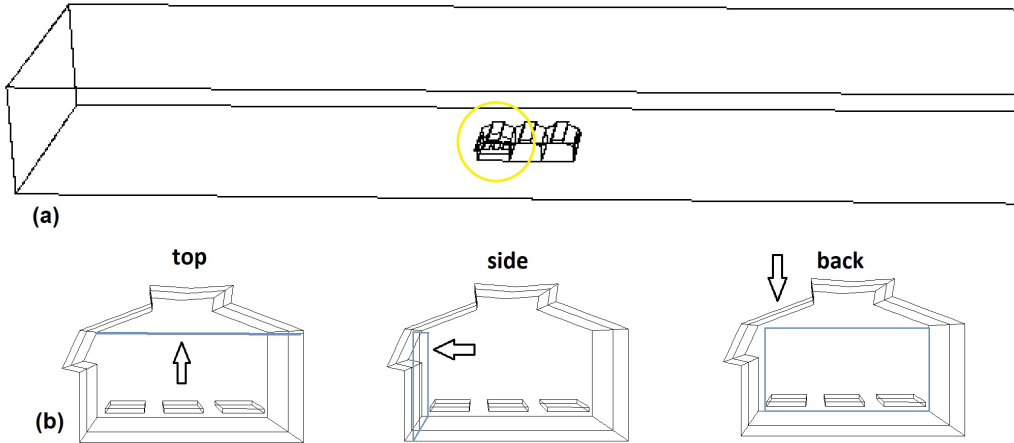


Figure 8: Image of the simulation domain and the screens positions: (a) is the simulation domain with the SE span of the greenhouse highlighted in yellow; (b) are the three positions of the screens inside the cultivation area of the SE span, highlighted in grey.

383 For all the sixteen combinations analyzed, the indoor environmental condi-  
384 tions in the productive area of the span highlighted in Figure 8, have been  
385 evaluated and reported in the following section.

### 386 3. Results and Discussion

387 The indoor velocity distribution obtained within the greenhouse, for the  
388 Scenario 1 (i.e. combinations from 1 to 4) are shown in Figure 9, by means of  
389 a vertical section based in the middle of greenhouse.

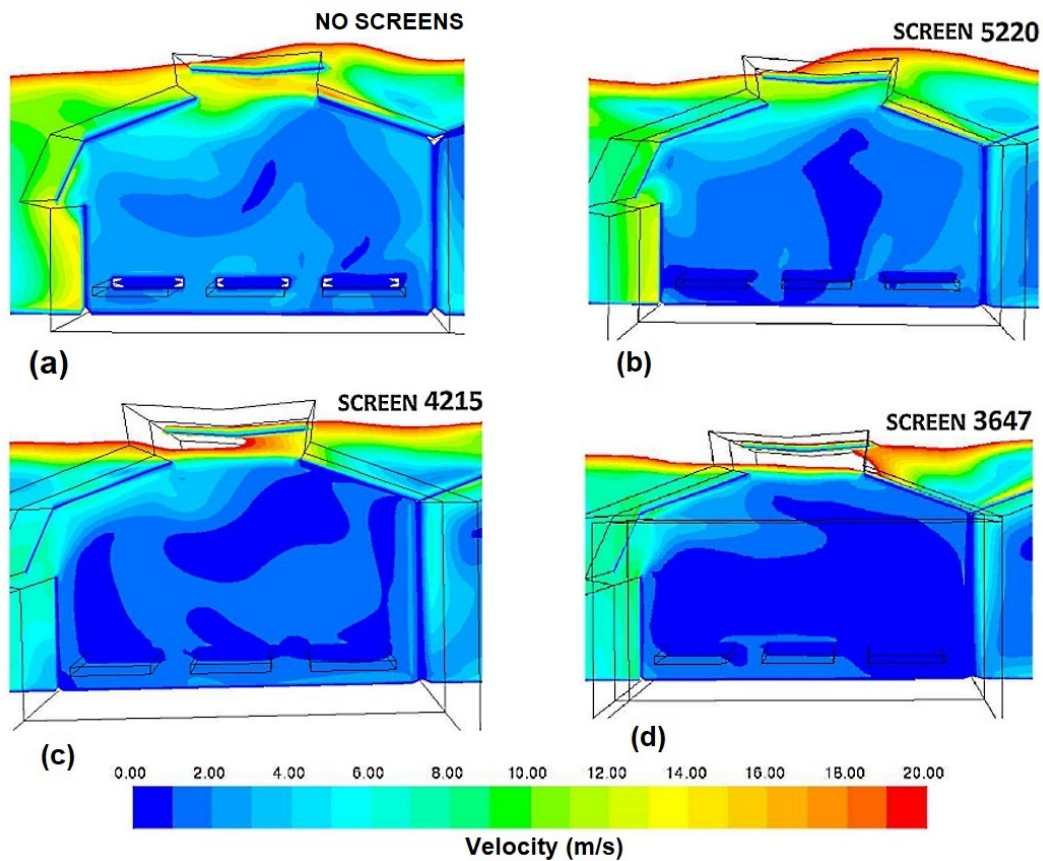


Figure 9: Contour of the air velocity magnitude distribution, on the middle vertical section of the cultivation area for the Scenario 1: (a) Combination 1; (b) Combination 2; (c) Combination 3; (d) Combination 4.

390 Figure 10 presents analogous results but for the Scenario 2. These scenarios  
 391 are characterized by similar outdoor conditions but differ in the wind direction.  
 392 The contour maps in Fig. 9 and 10 show the strong dependence of the velocity  
 393 distribution from the presence and, then from the type of screen. As also  
 394 obtained in other works, e.g. (Santolini et al., 2018), the presence of the  
 395 shading devices strongly affects the airflow distribution inside the structure.  
 396 The main effect of the screens, on the ventilation, is to reduce the mixing and  
 397 the velocity magnitude, also in case of strong solar radiation. Smaller is the  
 398 grid dimension of the screen and higher is the number of the impermeable  
 399 strips respect to the number of the porous one in the texture, generally lower  
 400 is the indoor magnitude velocity and enlarged are the areas of the section with  
 401 velocity almost zero, as clearly visible in Figure 9.

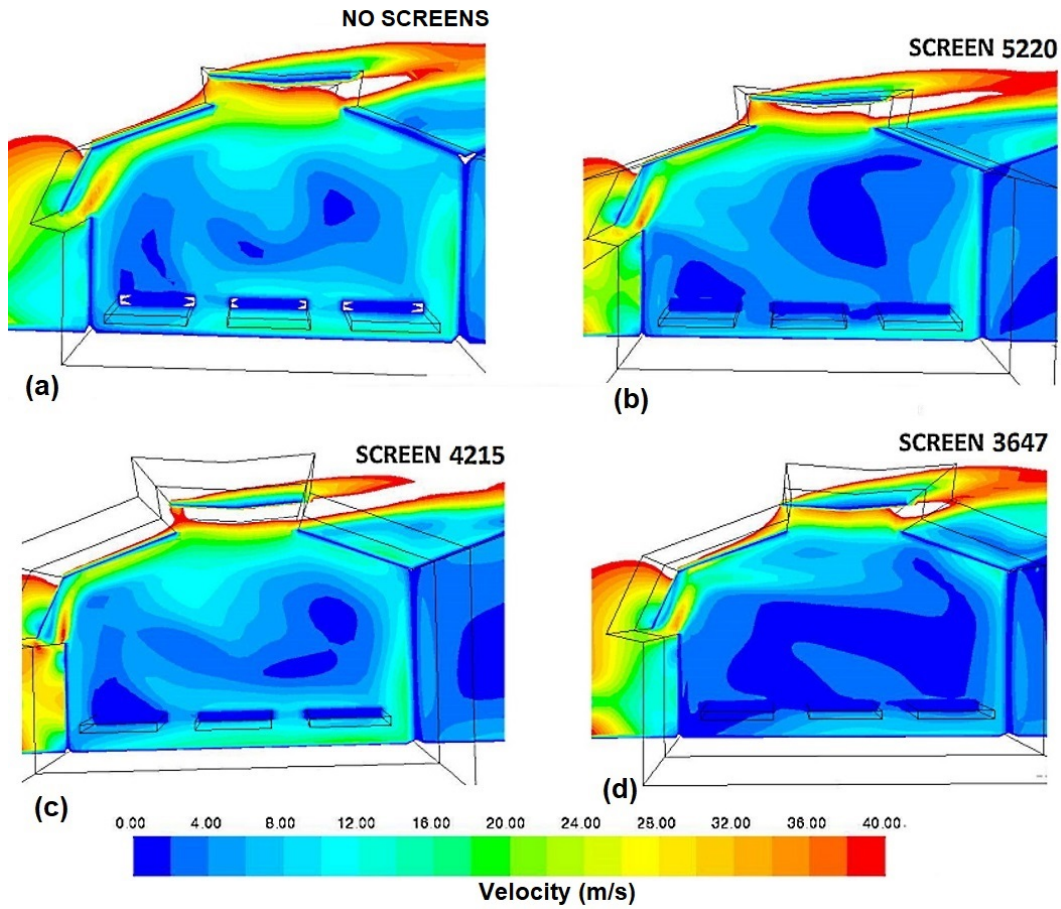


Figure 10: Contour of the air velocity magnitude distribution, on the middle vertical section of the cultivation area for the Scenario 2: (a) Combination 5; (b) Combination 6; (c) Combination 7; (d) Combination 8.

402 However, the negative action of screens, reducing the air velocity magni-  
 403 tude, doesn't raise if the incoming air velocity increases, as visible from the  
 404 comparison of the Scenario 1 and Scenario 2. This aspect highlights and con-  
 405 firms that inertial coefficient has a reduced impact on the airflow through the  
 406 porous surface when the air velocity in inlet is increasing, as supposed in San-  
 407 tolini et al. (2019). The results obtained for the case with wind blowing from  
 408 South-East (Scenario 2), where the wind has strong magnitude and it is per-  
 409 pendicular to lateral and roof vents. In this case, the effect of the screens, on  
 410 the velocity field, are considerably less relevant than in Scenario 1. In Fig-  
 411 ure 10, the variation of the air velocity magnitude and distribution due to the  
 412 presence of the screens is limited in all cases, particularly in presence of H4215.  
 413 Analogous air velocity contours have been obtained, obviously with different  
 414 magnitude order, for the Scenarios 3 and 4, and are not reported here for the  
 415 sake of paper brevity.

416 On the contrary, the temperature distributions inside the cultivation area, ob-  
 417 tained for the two Scenarios 1 and 2, are very different. Figures 11 and 12  
 418 show the temperature distribution obtained on a vertical section, for Scenario

419 1 and 2, respectively. Both scenarios show a rather homogeneous temperature  
 420 in the cultivation area, thanks to the presence of the screens.

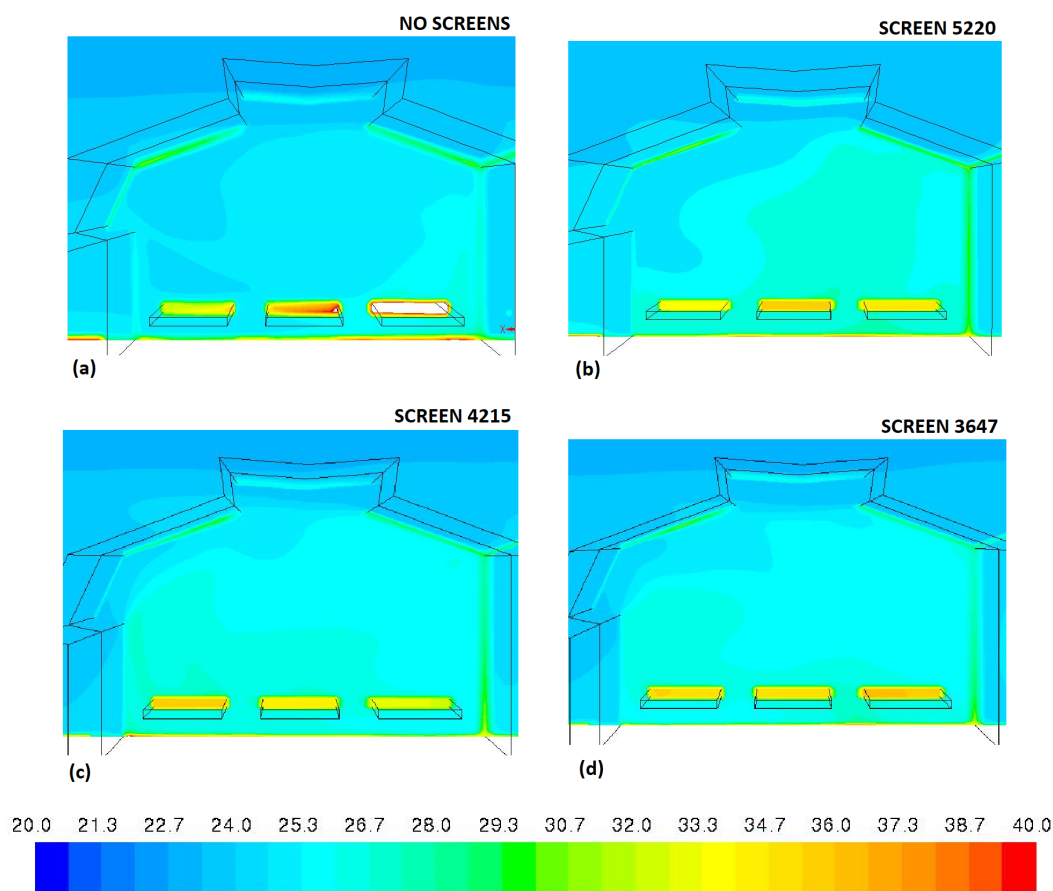


Figure 11: Contour of the temperature distribution, on the middle section of the cultivation area, of Scenario 1: (a) Combination 1; (b) Combination 2; (c) Combination 3; (d) Combination 4.

421 However, the two Scenarios show very different temperature reduction  
 422 ranges, within the cultivation area. The average temperature in Scenario 1,  
 423 in the cultivation area, is about 26.5 °C and is 23.5 °C in Scenario 2. Then,  
 424 the difference in terms of temperature reduction, between the two Scenarios,  
 425 is about 3 °C. In fact, in the Scenario 2 the wind velocity contribution in the  
 426 cultivation area is more consistent. Another interesting aspect, emerging in  
 427 the Scenario 2, is the effective mitigation of the temperature value of the first  
 428 bench on the left, close to the lateral window, provided by the shading devices.  
 429 A similar situation is visible also in the Scenario 1, where the worst condition  
 430 in terms of high temperature is provided by the internal bench (right bench in  
 431 the Figures 11), close to the internal wall separating two different spans, and  
 432 located far from the lateral window.

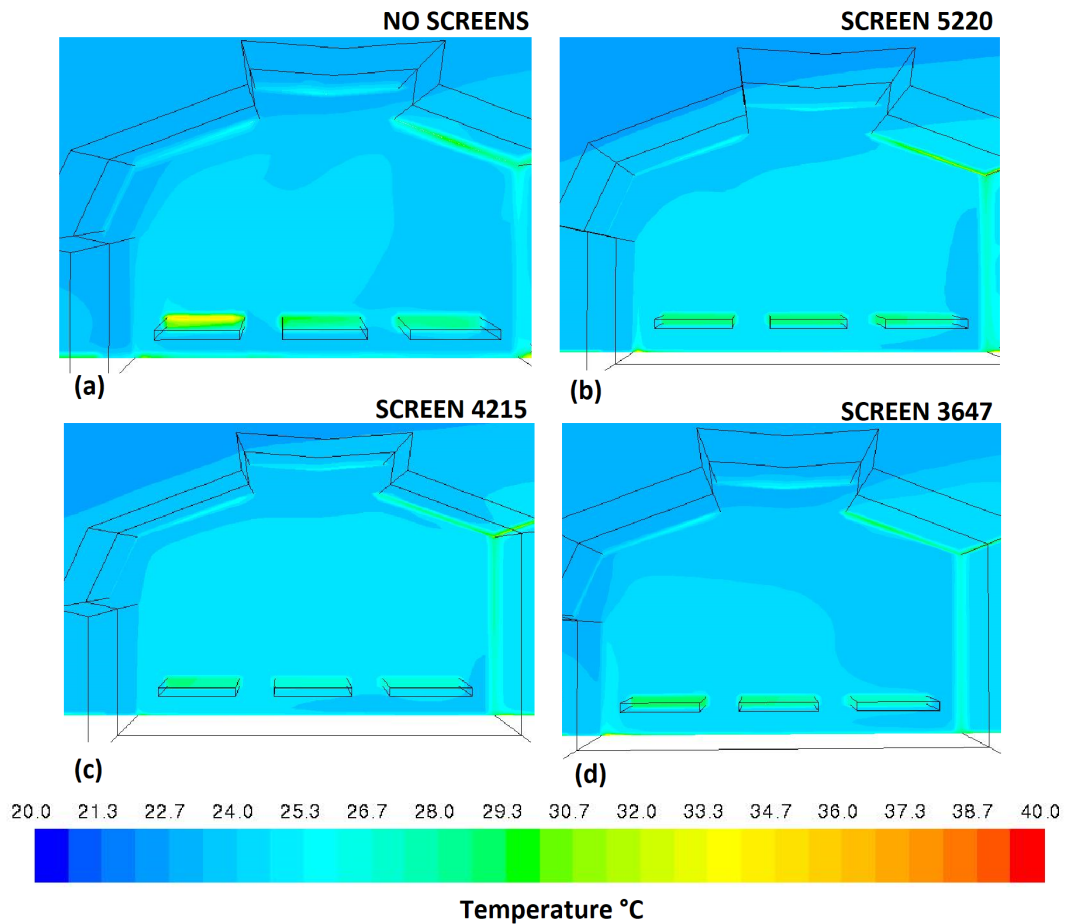


Figure 12: Contour of the temperature distribution, based on the middle section of the cultivation area, of Scenario 2: (a) Combination 5; (b) Combination 6; (c) Combination 7; (d) Combination 8.

433 Figure 11 and 12 show that shading devices will provide potential better  
 434 conditions for the crop growth because the temperature distribution is more  
 435 homogeneous in presence of the screens. The shading devices have a positive  
 436 effect not only in the cases of strong wind and limited solar radiation but also  
 437 in those cases with high solar radiation. Indeed, Figures 13 and 14 show the  
 438 temperature distribution on the middle vertical section, for Scenario 3 and  
 439 4, respectively. The temperature distribution obtained for Scenario 3 shows  
 440 homogeneous distribution together with average temperature values, higher  
 441 than temperature in Scenario 4. This outcome can be attributable to the  
 442 reduced action of the natural ventilation in the heat removal, due to both, the  
 443 unfavourable wind direction and reduced wind magnitude, in synergy with the  
 444 negative consequences of the screens presence.



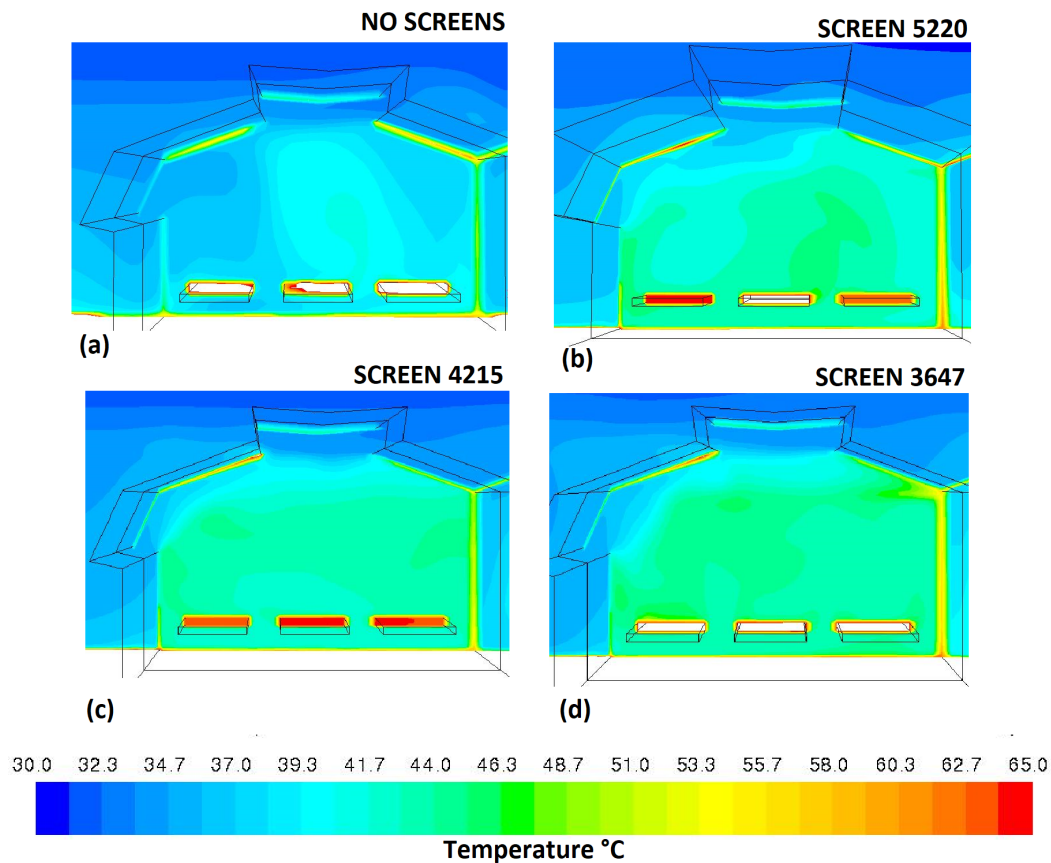


Figure 13: Contour of the temperature distribution, based on the middle section of the cultivation area of Scenario 3: (a) Combination 9; (b) Combination 10; (c) Combination 11; (d) Combination 12.

445 On the other side, in the Scenario 4, with the wind blowing from South-East  
 446 direction, the shading devices allow to create a rather homogeneous tempera-  
 447 ture distribution, around 35-37 °C, inside the structure, without the consistent  
 448 temperature increase showed in Figure 13 for the Scenario 3.  
 449 Focusing on the main aim of the use of the shading devices that is to maximize  
 450 the plant growth, two different conditions are important: the temperature over  
 451 the benches and the velocity value and distribution around the crops.

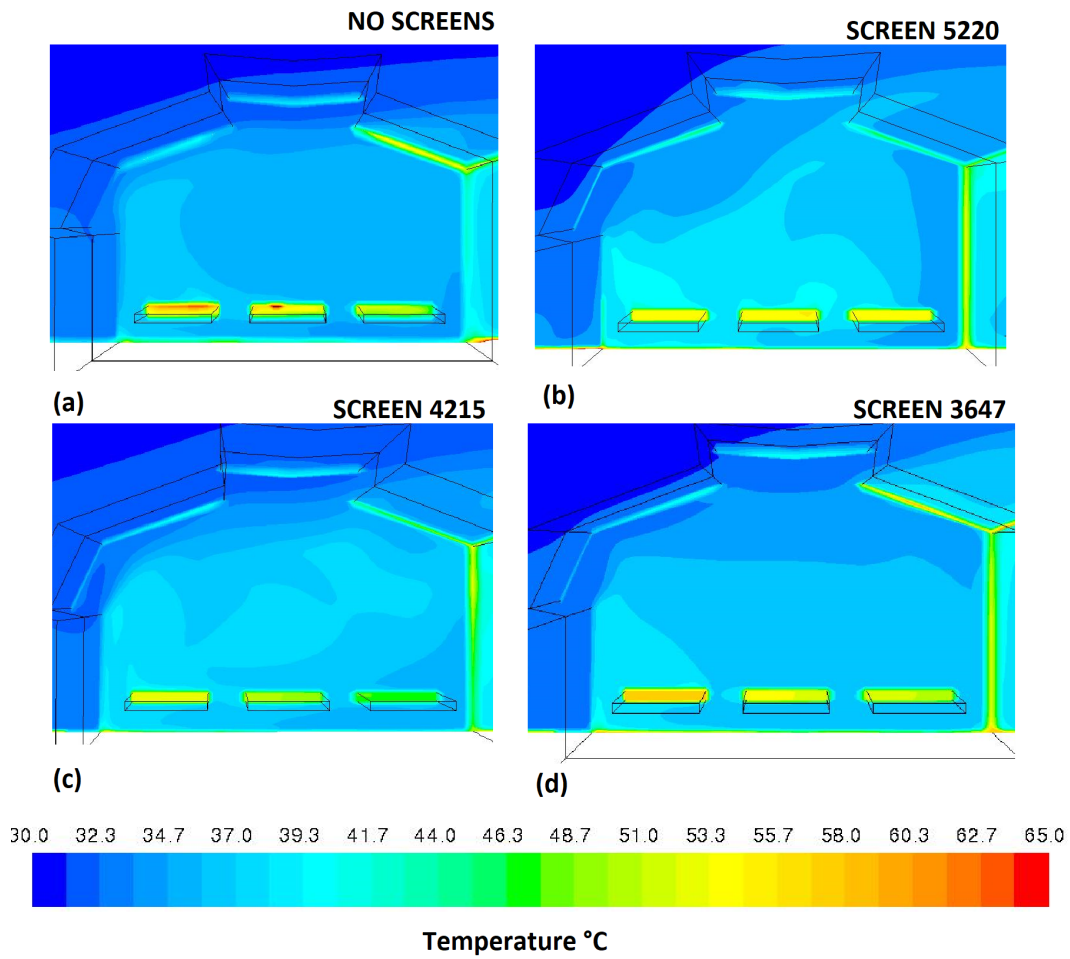


Figure 14: Contour of the temperature distribution, on the middle section of the cultivation area, of Scenario 4: (a) Combination 13; (b) Combination 14; (c) Combination 15; (d) Combination 16.

452 To this regard, firstly, the Scenarios 3 and 4 have been analysed. In Figure  
 453 15, the temperature distribution, at a distance of 10 cm from the benches, is  
 454 presented for Scenarios 3 and 4. The Figure 15 shows the remarkable benefits  
 455 of the introduction of the shading devices, in terms of both temperature level  
 456 and distribution, close to the crops.

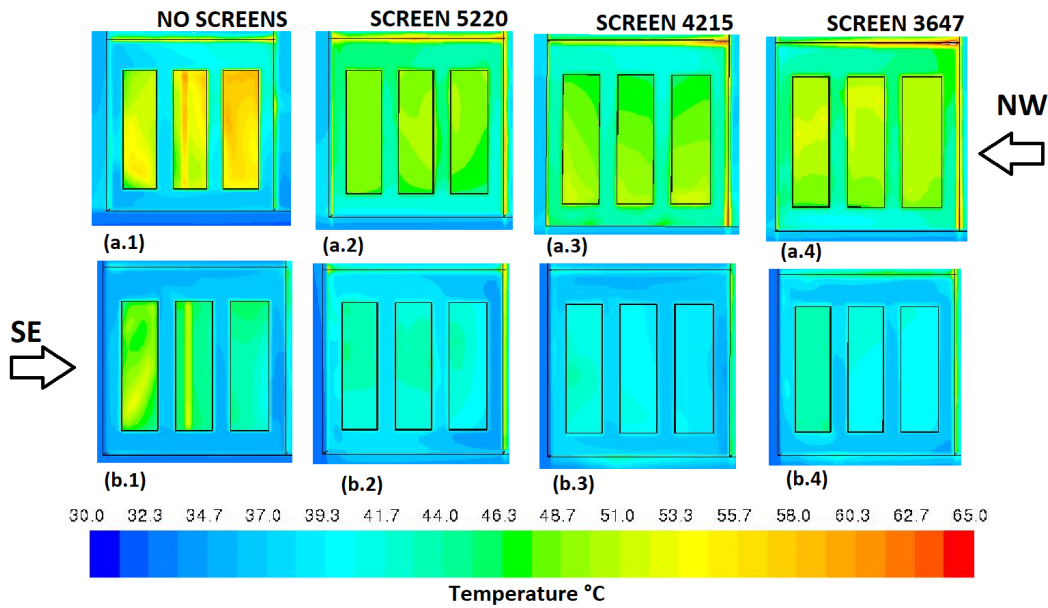


Figure 15: Contour of the temperature at the crop level: (a) Scenario 3; (b) Scenario (4).

457 In the case without screens (see No screens case), the first left bench, on  
 458 Scenario 3, and the third left bench, on Scenario 4, show the highest tem-  
 459 perature at the crop level together with a poorly homogeneous distribution.  
 460 The temperature distribution becomes homogeneous only in the sub cases with  
 461 screens. Obviously, the positive impact of the screens depends on type of screen  
 462 and on wind direction. The influence of every type of screen, with wind blow-  
 463 ing from NW, can be considered similar in terms of temperature magnitude,  
 464 but has slightly different temperature distributions. In presence of the screens  
 465 H5220 and H3647, the temperature distribution is rather homogeneous over  
 466 all the cultivation benches. On the contrary, the screen H4215 creates an area,  
 467 closer to the back wall of the greenhouse, with a slightly greater temperature.  
 468 Different conditions can be noticed in case of wind blowing from SE, because  
 469 the screens H4215 and H3647 have a stronger influence in reducing the tem-  
 470 perature values, if compared to H5220 screen.

471 When the wind magnitude is higher and the solar radiation effects is limited,  
 472 the temperature distributions over the benches are similar if screens are intro-  
 473 duced in the building, as showed in Figure 16. For these cases, the different  
 474 screens have similar influence on temperature magnitude and distribution.



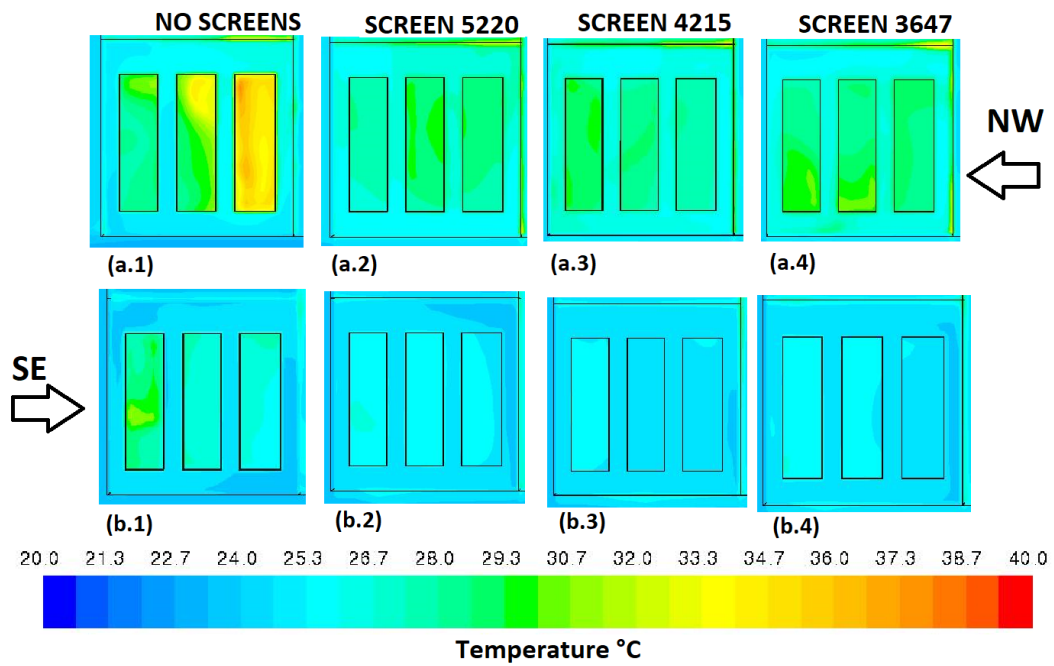


Figure 16: Contour of the temperature at the representative level: (a) Scenario 1; (b) Scenario 2.

475 Moreover, the temperature mitigation is less dependent on wind direction.  
 476 These results are analysed in detail in Figure 17. The values reported in Figure  
 477 17 are the peak values obtained for each one of the 16 combinations at the level  
 478 of 10 cm over the benches. The temperature reductions reported, instead, are  
 479 obtained from the values in Figure 16 as difference between the value of the  
 480 case considering a particular screen and the "no screens" case.

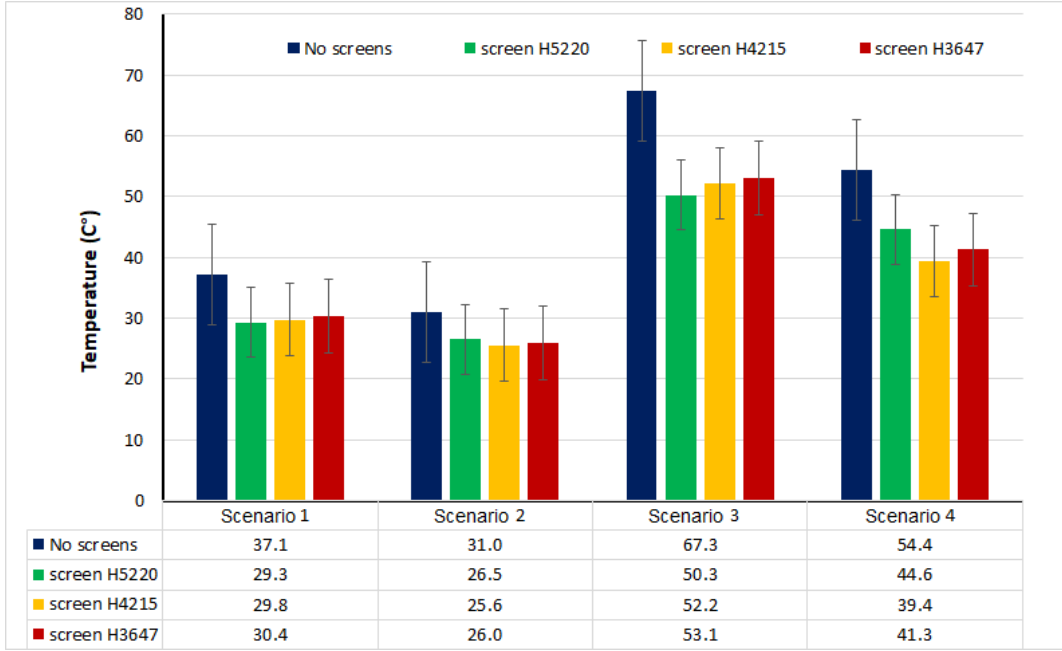


Figure 17: Peak temperature obtained for the various scenarios 10 cm over the bench level.

481 The H5220 screen allows to obtain a temperature reduction value ranging  
 482 from 4.5 °C and 17 °C, with an average value around 9.8 °C. The temperature  
 483 reduction achievable with the H4215 and H3647 are similar: it ranges from 4.5  
 484 °C to about 15 °C with average value about 5 °C. The temperature mitigation  
 485 index,  $\delta_T$ , have been been calculated by Eq. 14 for the three screens in the four  
 486 scenarios, as reported in Table 5. The mean value for each screen has been  
 487 estimated in order to identify a single index representative of the mitigation  
 488 effect of each screen.

$$\delta_T = \frac{T_{max,noscreen} - T_{max,screen}}{T_{max,noscreen}} \quad (14)$$

489 where  $T_{max,noscreen}$  is the peak of temperature in a specific scenario without  
 490 screen and  $T_{max,screen}$  is the peak of temperature in a specific scenario with a  
 491 specific screen.

Table 5: Quantified temperature mitigation operated by each screen in a specific scenario by means of the  $\delta_T$  index.

	H5220	H4215	H3647
Scenario	$\delta_T$	$\delta_T$	$\delta_T$
1	0.21	0.197	0.18
2	0.16	0.174	0.16
3	0.253	0.224	0.211
4	0.18	0.276	0.241
mean	0.2	0.22	0.2

492 The screens show similar mitigation effects in three of the four scenar-  
 493 ios. However, in the scenario 4 (high solar radiation and moderate wind ve-  
 494 locity) the H5220 screen is characterized by a significantly important effect  
 495 which is 1.5 and 1.3 times higher than the case with H4215 and H3647 re-  
 496 spectively. The temperature reduction obtainable from each screen strongly  
 497 depends on the external climate conditions. In fact, the final mitigation index  
 498 shows marginal differences between the three devices, confirming anyway that  
 499 H5220 and H3647 are slightly more efficient.

500 Finally, the analysis of the temperature trends for the various combinations  
 501 along the vertical axis, can be useful to evaluate the effects of the screen  
 502 presence and to assess the temperature homogeneity for increasing level in  
 503 order to estimate the possible effects on crops with different height. The peak  
 504 temperatures detected for different levels from 10 to 30 cm over the benches  
 505 are depicted in Figure 18 for Scenarios 3 and 4.

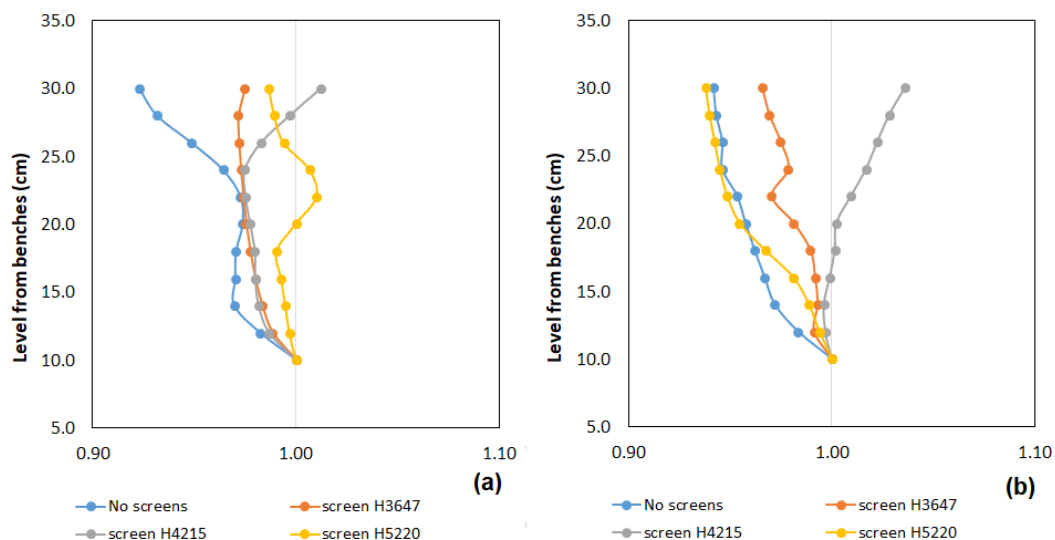


Figure 18: Comparison of the peak temperature trends for different combinations at different heights over the benches: (a) Scenario 3 and (b) Scenario 4.

506 In the figure, the values are normalized by the value observed at the refer-  
 507 ence level explained before and equal to 10 cm over the benches. The first graph  
 508 shows the peak temperatures trends of the Scenario 3. The temperatures of  
 509 the combinations with shading devices have, in general, a more homogeneous  
 510 trends if compared with the case without screens ("No screens" case) since the  
 511 values are usually closer to the unitary value.

512 Analogously, in Figure 18(b) are showed the trends for the Scenario 4. Also  
 513 in this case, the adoption of the screens, improves the air temperature homo-  
 514 geneity at all the levels investigated, confirming the effectiveness of the shading  
 515 devices in the mitigation of this type of problem in the greenhouse cultivation.  
 516 Similar consideration could be found for the Scenario 1 and 2. They are not  
 517 reported here for brevity reasons.

518 Since the considerations for the optimal conditions for plant growth usu-  
 519 ally must take into account temperature and air velocity distributions, the  
 520 temperature and the air velocity magnitudes have been compared based on  
 521 their average values, obtained for seven levels in the cultivation area. Then,  
 522 seven sections from 10 to 30 cm over from the cultivation benches have been  
 523 considered for the analysis. In Figure 19, blue bars are referring to the tem-  
 524 perature values while red bars refer to the air velocity magnitudes.

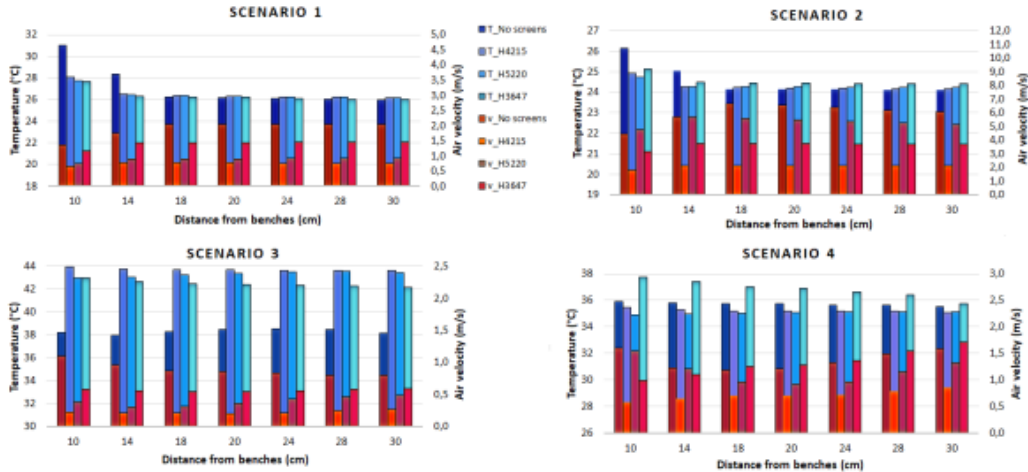


Figure 19: Comparison between the results of averaged temperature and air velocity, at several levels, for all scenarios and combinations.

525 In the Scenario 1, a considerable temperature reduction is provided by the  
 526 three screens in the first and in the second section. On the other hand, the  
 527 air velocity is considerably affected by the screens presence. In this scenario,  
 528 the H3647 screen demonstrates the best mitigation effects on the temperature,  
 529 maintaining a good ventilation, i.e. a good air velocity, in the cultivation area.  
 530 Similar results can be noticed for the Scenario 2, where the H3647 screen shows  
 531 good performances. However, in this scenario, the best temperature reduction  
 532 with highest level of ventilation is usually provided by the H5220 screen. On  
 533 the contrary, in case of strong incident solar radiation and wind blowing with  
 534 low velocity from a critical direction, i.e NW, (scenario 3), all the screens  
 535 demonstrates to be ineffective on the temperature while worsening the air flow  
 536 distribution. Finally, in Scenario 4, the H4215 and H5220 are able to provide  
 537 a good improvement of the temperature values. On the contrary, in this sce-  
 538 nario, the H3647 screen has globally a negative performance. In this last case,  
 539 the best performance is to attribute to the H4215 screen. Considering the  
 540 results as a whole, the screen H4215 and H5220 demonstrated similar effects  
 541 on the indoor environment for three cases out of four, despite their significant  
 542 differences in texture and physical properties. Concluding, the shading devices  
 543 with a with visible porosity in the texture and characterized by good radiative  
 544 performances represent the best shading solution for the analysed case study.  
 545 A screen with low permeability like the H5220 gives better performances if

546 used in situations where the wind does not hit the wall directly. On the other  
547 hand, in situations where the wind hits the walls directly, screens with higher  
548 permeability like the H4215 give better performances.

549

#### 550 **4. Conclusions**

551 The shading devices are one of the most used solution, in protected crop  
552 structures, to mitigate the effects of solar radiation, especially in the sunny  
553 days during the hot season in Mediterranean area. They are usually placed  
554 internally, over the cultivation area, in order to positively affect the incident  
555 radiation and to create better conditions for the crop growth. In fact, the  
556 presence of shading devices can significantly modify the indoor environmental  
557 conditions. However, they affect not only the solar radiation but also the air  
558 flow distribution, because they can considerably reduce the indoor air velocity,  
559 especially if they have a low porosity texture. In this paper, the combinations  
560 of the reduction of the solar radiation with the modification of the flow ve-  
561 locity given by three different shading screens have been analysed. Different  
562 outdoor environmental conditions have been considered, in order to consider  
563 combinations of low solar radiation and different wind velocity and directions.  
564 The choice of a specific shading device is very important because it allows to  
565 create more suitable conditions for the crop cultivation. The same considera-  
566 tions can be performed on the air flow distribution. The indoor temperature  
567 distribution has been obtained for different scenarios, in term of maximum  
568 temperature achieved together with a low variability above the crops. The  
569 performances of each screen have been compared and correlated with the envi-  
570 ronmental conditions. The results show that screens with low permeability like  
571 the H5220 and the H4215 give optimal temperature mitigation together with  
572 a uniform temperature distribution above the crops. However, screens with  
573 higher permeability give better performances in situations where the wind hits  
574 the walls directly. The best choice, for the case considered in this paper, is the  
575 H4215, *i.e.* a screen with a permeability equal to  $0.58 \text{ m}^{-1}$ . This means that  
576 the choice of the best screen must be done considering also the most frequent  
577 conditions in terms of wind directions with respect to orientation and position  
578 of the windows in the greenhouse.

#### 579 **Appendix**

580 The method of solving the 3D trilateration problem used in this work, *i.e.*  
581 how to find the position in the space of a target point knowing its distance  
582 from four known points, is now enunciated. To find the intersection point  
583 of the four spheres it is necessary to solve a system of four equations with  
584 four unknowns. To simplify the computational procedure, making it usable  
585 even in poor computers or micro-controllers, it will be solved a system of three  
586 equations in three unknowns, taking into account only three of the four spheres,

587 obtaining in this way two possible solutions. Applying this procedure to the  
 588 four possible combinations of three of the four spheres, a unique solution will  
 589 be obtained.

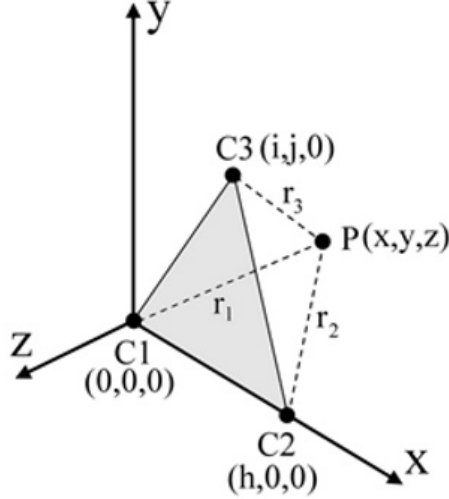


Figure 20: Three spheres centers ( $C_1, C_2, C_3$ ) and target point (P).

590 In the equations 11a,11b and 11c the coordinates (x, y, z) describe the  
 591 unknown position of the microphone P (target); the coordinates ( $x_1, y_1, z_1$ ),  
 592 ( $x_2, y_2, z_2$ ) and ( $x_3, y_3, z_3$ ) describe the known positions of the centers of the  
 593 three spheres  $C_1, C_2$  and  $C_3$  considered for the calculations; the radii  $r_1, r_2$   
 594 and  $r_3$  are the known distances (radii of the spheres  $C_1, C_2$  and  $C_3$ ) between  
 595 the target position P and the centers of the mentioned spheres.

596 The system is described by the equations:

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = r_1^2 \quad (15a)$$

597

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = r_2^2 \quad (15b)$$

598

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = r_3^2 \quad (15c)$$

599 A new coordinate system is now defined, as shown in Figure 20, used  
 600 temporarily to solve the system of equations in 15a15b15c. The origin of the  
 601 new system, at coordinates (0,0,0), is placed at the center of sphere  $C_1$ ; the  
 602 center of sphere  $C_2$  is placed at (h,0,0); the center of sphere  $C_3$  is placed at  
 603 (i,j,0). The centers of the spheres are therefore all on the same plane xy.

604 The vectors that define the base of the new coordinate system are:

$$\hat{e}_x = \frac{\bar{p}_2 - \bar{p}_1}{\|\bar{p}_2 - \bar{p}_1\|} \quad (16a)$$

605

$$\hat{e}_y = \frac{(\bar{p}_3 - \bar{p}_1) - \hat{e}_x \cdot (\hat{e}_x \cdot (\bar{p}_3 - \bar{p}_1))}{\|(\bar{p}_3 - \bar{p}_1) - \hat{e}_x \cdot (\hat{e}_x \cdot (\bar{p}_3 - \bar{p}_1))\|} \quad (16b)$$

606

$$\hat{e}_z = \hat{e}_x \times \hat{e}_y \quad (16c)$$

607 The centers of the three spheres  $C_1$ ,  $C_2$  and  $C_3$  are defined, in the new  
608 coordinate system, as:

$$609 C_1 : \bar{p}_1 = (x_1, y_1, z_1)$$

$$610 C_2 : \bar{p}_2 = (x_2, y_2, z_2) = \bar{p}_1 + \hat{e}_x h$$

$$611 C_3 : \bar{p}_3 = (x_3, y_3, z_3) = \bar{p}_1 + \hat{e}_x i + \hat{e}_y j$$

612

613 being:  $h = \hat{e}_x \cdot (\bar{p}_2 - \bar{p}_1)$ ,  $i = \hat{e}_x \cdot (\bar{p}_3 - \bar{p}_1)$ ,  $j = \hat{e}_y \cdot (\bar{p}_3 - \bar{p}_1)$ .

614

615 The equations 16a 16b 16c in the new coordinate system are:

$$(X_n)^2 + (Y_n)^2 + (Z_n)^2 = r_1^2 \quad (17a)$$

616

$$(X_n - h)^2 + (Y_n)^2 + (Z_n)^2 = r_2^2 \quad (17b)$$

617

$$(X_n - i)^2 + (Y_n - j)^2 + (Z_n)^2 = r_3^2 \quad (17c)$$

618 In the equations 17a, 17b and 17c, the variables x, y and z are renamed  
619 as  $X_n$ ,  $Y_n$  and  $Z_n$  to avoid confusion with the original coordinate system. The  
620 two solutions of Eq. 17a, 17b and 17c are therefore:

$$X_n = \frac{r_1^2 - r_2^2 + h^2}{2h} \quad (18a)$$

621

$$Y_n = \frac{r_1^2 - r_3^2 + i^2 + j^2 - 2iX_n}{2j} \quad (18b)$$

622

$$Z_n = \pm \sqrt{r_1^2 - X_n^2 - Y_n^2} \quad (18c)$$

623

The two solutions, rewritten in the original coordinate system, are:

$$\text{Solution1} : \bar{p}_a = \bar{p}_1 + \hat{e}_x X_n + \hat{e}_y Y_n + \hat{e}_z Z_n \quad (19)$$

$$\text{Solution2} : \bar{p}_b = \bar{p}_1 + \hat{e}_x X_n + \hat{e}_y Y_n - \hat{e}_z Z_n \quad (20)$$

624 The two solutions found are symmetrical to the plane on which the centers  
625 of the three spheres are located. In GitHub, a C++ public domain code for  
626 the resolution according to the described method can be found. It remains to  
627 be determined which of the two solutions found is the real one. The described  
628 procedure is repeated to cover all possible combinations of intersections of four  
629 spheres, taken three at a time. The number of required combinations is (n =

630 4,  $k = 3$ ):

$$\frac{n!}{k!(n-k)!} = \frac{4!}{3!(4-3)!} = 4 \quad (21)$$

631 By renaming  $S_1, S_2, S_3$  and  $S_4$  the four spheres, the possible combinations  
632 are:  $(S_1, S_2, S_3)$ ,  $(S_1, S_2, S_4)$ ,  $(S_1, S_3, S_4)$  and  $(S_2, S_3, S_4)$ . By solving the prob-  
633 lem four times, considering the above mentioned combinations of spheres, four  
634 pairs of solutions are obtained. In each pair only one exact solution exists, so  
635 by examining all four pairs of solutions, the real solution will be the one that  
636 appears in all the four cases.

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