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Climatized packing house with evaporative coolers - Part 2: Geostatistical mapping[1]

Packing house climatizado com resfriadores evaporativos - Parte 2: Mapeamento geoestatístico

Isadora B. Miranda[2*], Ítalo E. dos A. Santos[3], Magno do N. Amorim[4], Silvia H. N. Turco[3] & Ana C. de S. S. Lins[5]

[1] Research developed at Casa Nova, BA, Brazil
[2] Universidade Federal de Campina Grande, Campina Grande, PB, Brazil
[3] Universidade Federal do Vale do São Francisco, Juazeiro, BA, Brazil
[4] Universidade de São Paulo/Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, SP, Brazil
[5] Universidade Federal de Lavras, Lavras, MG, Brazil

HIGHLIGHTS:

Evaporative coolers improve thermal comfort for workers in hot and dry climates.
The application of geostatistics allowed the assessment of necessary interventions in the study environment.
It is essential to size the number of evaporative coolers appropriately to achieve homogenization of the environment.

ABSTRACT: The acclimatization of packing houses is essential for human well-being, and, as it is a production environment, it is desirable that environmental variables are homogeneous. Therefore, this study was conducted with the aim of evaluating the environment in the selection and packaging area of a climate-controlled grape packing house with an evaporative cooling system, characterizing the spatial thermal variability and identifying critical control points. The climatic variables temperature, relative humidity and wind speed were analyzed, at 10:00, 13:00 and 15:00 h during the dry and rainy seasons. Two treatments were evaluated: with evaporative coolers switched on and switched off. The spatial distribution of the variables was mapped by kriging. The evaporative cooling system improved the thermal conditions in the selection and packaging area of the packing house but did not ensure homogenization. Critical points were identified at the beginning of the processing line, in a region further away from the coolers. The use of geostatistics and kriging maps made it possible to identify the spatial variability of climatic attributes and localize problematic regions, which allowed targeted corrections to be made to the factors that compromise human thermal comfort.

Key words: ambience, fruit processing, thermal comfort, kriging, spatial variability

RESUMO: A climatização de packing houses é fundamental para o bem-estar humano, e por se tratar de um ambiente de produção, é desejável que haja homogeneidade das variáveis ambientais. Assim, este estudo foi conduzido com o objetivo de avaliar o ambiente na área de seleção e embalagem de um packing house de uvas de mesa climatizado com sistema de resfriamento evaporativo, caracterizar a variabilidade térmica espacial e identificar pontos críticos de controle. As variáveis climáticas temperatura, umidade relativa e velocidade do vento foram avaliadas nos períodos seco e chuvoso, às 10:00, 13:00 e 15:00 h. Foram avaliados dois tratamentos: com os resfriadores evaporativos ligados e desligados. A distribuição espacial das variáveis foi mapeada por krigagem. O sistema de resfriamento evaporativo melhorou as condições térmicas na área de seleção e embalagem do packing house, mas não garantiu a homogeneização. Pontos críticos foram identificados no início da linha de beneficiamento, uma região mais distante dos resfriadores, marcada à direita nos mapas de krigagem. O uso da geoestatística e dos mapas de krigagem permitiu identificar a variabilidade espacial dos atributos climáticos e localizar regiões problemáticas, possibilitando correções pontuais para fatores que comprometem o conforto térmico humano.

Palavras-chave: ambiência, beneficiamento de frutas, conforto térmico, krigagem, variabilidade espacial

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* Corresponding author - E-mail: isadorabenevidesmiranda@gmail.com
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Introduction

The Submédio Vale do São Francisco region stands out in Brazilian fruit cultivation. However, the climatic conditions have an unfavorable effect on the thermal well-being of agricultural workers, including those who work within enclosed spaces such as packing houses (Miranda et al., 2025).

Thermal discomfort can also arise when exposed to lower temperatures (Yin et al., 2021), especially when it comes to people who are not used to specific climatic conditions. Consequently, among the different types of air conditioning systems it is important to find the one that best suits the local climatic conditions and offers an optimal cost-benefit ratio for the rural entrepreneur, such as the evaporative cooling system.

In production environments, it is desirable to achieve homogeneity of environmental variables, which can be assessed by spatialization and geostatistical tools. Spatial analysis of climatic data allows the identification of areas experiencing thermal stress, facilitating decisions on appropriate environmental management and the recommendation of thermal conditioning practices (Massari et al., 2016; Ribeiro et al., 2016).

Geostatistical techniques, together with map creation, are used in precision ambience studies, to increase the precision of environmental interpretation and allow better visualization of critical control points (Gonçalves et al., 2016; Queiroz et al., 2017; Rodrigues et al., 2020; Faustino et al., 2021; Guesine et al., 2023).

Therefore, this study was conducted with the aim of evaluating the environment in the selection and packaging area of a climate-controlled grape packing house with an evaporative cooling system, characterizing the spatial thermal variability and identifying critical control points.

Material and Methods

The study was conducted in the municipality of Casa Nova, Bahia, Brazil (9° 9' 43" S and 40° 58' 15" W, altitude 397 m). According to the Köppen-Geiger classification, the climate of the region is classified as BSwh', which is characterized as very hot and dry, with an average annual precipitation of less than 500 mm, concentrated in three or four months.

The data were collected in the selection and packaging area of a grape packing house of a medium-sized commercial farm. Data collection took place during two production periods: in November 2019, with higher temperatures and low precipitation, considered as the dry season (D) in this study; and in March 2020, with milder temperatures and higher precipitation values, considered as the rainy season (R). Figure 1A illustrates the minimum

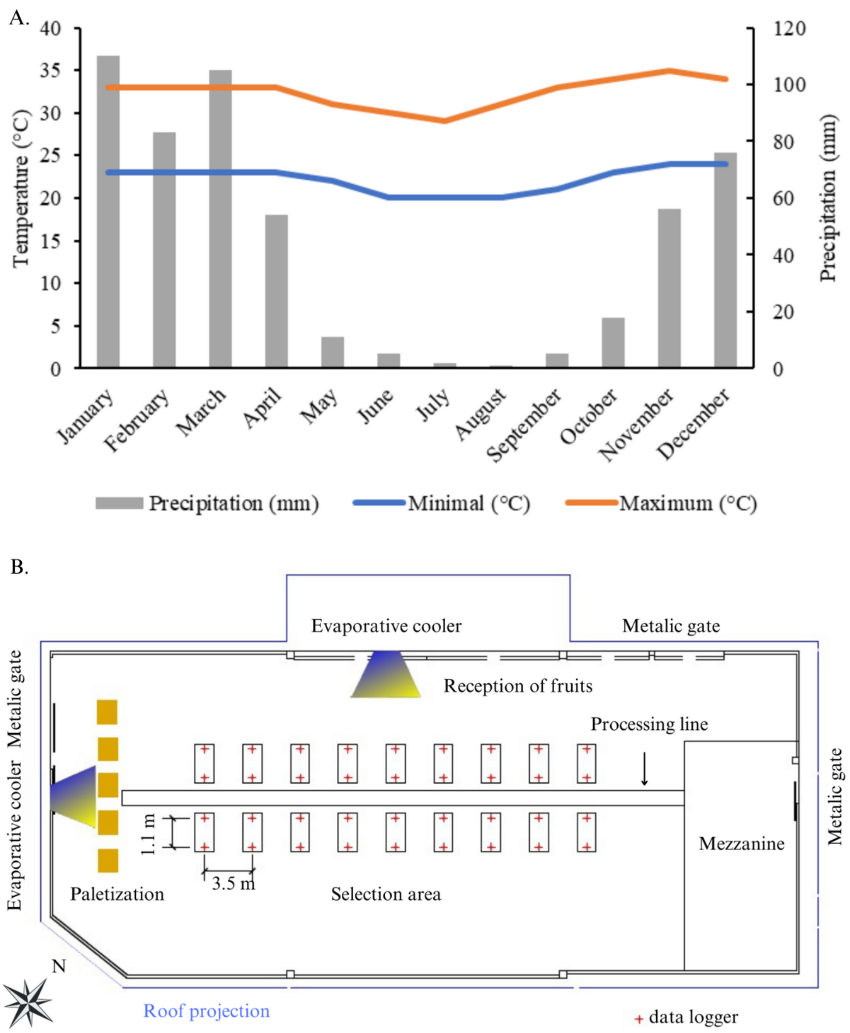

Figure 1. Characteristics of the study site: climatic data for the municipality of Casa Nova, Bahia (A) and the packing house layout (B)

and maximum air temperatures and precipitation values over the last 30 years.

In both winter and summer, the afternoon sunlight is projected inside the facility during the afternoon, especially in the region at the end of the processing line, where there is a meshed metal gate that allows this incidence (Figure 1B).

The packing house structure is made of reinforced concrete, with masonry for external enclosures and internal partitions, and a metal roof divided into three parts: an arch (in the center) and two in waterfall style for the sides, with a height of 4.0 m. It has 12 wind-driven roof ventilators with a height of 0.63, a width of 0.90 m at their widest, and 0.57 m at the end. There are 2 also evaporative coolers, both with a power of 1.3 kW h^{-1}, an air flow rate of 36,000 m^3 h^{-1}, and an effective coverage area ranging from 180 to 280 m^2. Meshed metal doors are present on three edges to facilitate the airflow in the environment.

Data for air temperature (T), relative humidity (RH), and wind speed (W) were collected under two conditions: with evaporative coolers (C ON) and without the coolers (C OFF) at 10:00, 13:00 and 15:00 h at 36 points in the selection and packaging area (3.3 × 28 m), arranged in a 1.1 × 3.5 m grid. Measurements were taken at height of 1.5 m from the ground at each grid point along the processing line (Figure 1B). Spatial variability assessment maps were created to identify areas of higher and lower values for the studied variables and to precisely control the necessary interventions in the evaluated environment.

Air temperature and humidity data were recorded using Hobo U12-013 data loggers (Onset Computer Corporation, Pocasset, MA, United States) with temperature measurement range between -20 and 70 °C and an accuracy of +/- 0.35 °C, and relative air humidity between 5 and 95%, with an accuracy of +/- 2.5%. The data loggers were fixed on metal structures on the workbenches.

Wind speed data were recorded using a hot-wire anemometer model tafr-190 (Instrutherm Instrumentos de Medição Ltda, São Paulo, SP, Brazil) with a measurement range between 0.1 and 25.0 m s^{-1}.

The variables T, RH, and W were assessed through descriptive statistical analysis, in which the mean, median, coefficient of variation (CV) classified as low when CV < 12%, medium when 12% < CV <24%, and high when CV > 24% (Warrick & Nielsen, 1980) and the coefficients for skewness and kurtosis were calculated. The Shapiro-Wilk normality test was applied at $p \leq 0.05$. The Sisvar 5.7 computational program was used for these analyses.

Spatial dependence was verified through semivariogram adjustments (Vieira, 2000), assuming an intrinsic stationary process, estimated by Eq. 1:

$$\gamma = \frac{1}{2N(h)} \sum_{i-1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (1)$$

where:

N(h) - number of experimental pairs; and,

$Z(x_i)$ and $Z(x_i+h)$ - observations separated by a distance h (m).

To fit the semi variogram, the highest coefficient of determination (R^2), the lowest sum of squared residuals (SQR), and the highest value of the spatial dependence degree (SDD), provided by the GS+ 7.0 software were considered. To analyze the degree of spatial dependence of the variables under study, Cambardella et al. (1994) classification was used, which considers a strong dependence for SDD of more than 0.75, a moderate dependence between 0.25 and 0.75, and a low dependence for a relation less than 0.25.

The theoretical semivariogram models considered in the study were spherical, exponential, linear, and Gaussian. Subsequently, these models were used to estimate the data at the unmeasured points using the interpolation method known as ordinary kriging. Finally, the maps were formatted and edited in Surfer® 13.0 software.

Results and Discussion

The average air temperatures were higher in the afternoon hours (13:00 and 15:00 h) in the selection and packaging area than at 10:00 h (Table 1). This is attributed to the lower incidence of direct solar radiation in the facility during the morning, a pattern observed in both the dry and rainy periods.

The use of evaporative coolers led to a reduction in temperature of up to 2 °C, both in the dry and rainy periods during the afternoon hours, which were the most critical conditions. This value is in close proximity to the findings of Faria et al. (2008), who observed a temperature reduction of up to 3.5 °C in a climate-controlled shed with an evaporative cooling system.

In all periods and treatments, the temperature showed a low coefficient of variation (CV), according to the methodology proposed by Warrick & Nielsen (1980), with 2.26 % being the highest value. This proves the homogeneity of the data and shows that the mean is a representative descriptive measure. Lopes et al. (2020) and Gonçalves et al. (2016) also observed a low CV for air temperature when investigating the spatialization of physical air variables in rural installations located in semi-arid regions.

The mean and median were similar, indicating that the data has no significant skewness, characterizing a normal distribution of the data, which is confirmed by the Shapiro-Wilk test with a probability of 5%. If the mean, median, and mode values are similar, this means that the data is normal or close to a normal distribution.

The average values of relative humidity were higher in the morning hours in both periods evaluated, with and without the cooler units (Table 1). This was to be expected, as the lowest temperature values were measured during this time.

In the dry period, higher relative humidity values were observed with the use of coolers, reaching 51.97% at 15:00 h, an increase of 26.35% when compared to the same period and time without the use of coolers (41.13%).

In the rainy period, the highest variation in relative humidity when comparing the treatments also occurred in the afternoon. However, the variation was only 5.52%, because at 13:00 h, the humidity levels for the C OFF and C ON treatments was 63.42 and 66.92%, respectively. This was due to the fact that the outside air already had a high humidity content. According to Raza et al. (2021), the performance of evaporative coolers

Table 1. Descriptive statistics of temperature (T), relative humidity (RH), and wind speed (W) in the selection and packaging area of the packing house during dry and rainy seasons, with evaporative coolers switched on and off

Variable	Period	Treatment	Time (hours)	Mean	Median	CV (%)	C_s	C_k	W
T (°C)	Dry	C OFF	10:00	27.18	27.15	0.84	0.37	1.38	0.31
			13:00	31.73	31.76	0.79	-0.19	1.26	0.73
			15:00	34.07	34.04	0.55	0.51	0.71	0.16
		C ON	10:00	26.57	26.58	0.94	-0.14	0.00	0.61
			13:00	30.51	30.55	1.06	-0.21	-0.73	0.39
			15:00	31.82	31.83	1.56	-0.34	-0.80	0.10
	Rainy	C OFF	10:00	28.64	28.62	0.68	0.47	0.20	0.52
			13:00	31.75	31.77	0.77	0.16	0.74	0.88
			15:00	32.23	32.24	0.95	-2.51	12.34	0.00*
		C ON	10:00	27.85	27.85	1.73	-0.51	-0.55	0.05
			13:00	29.82	29.87	2.26	-0.63	-0.59	0.02*
			15:00	30.26	30.34	2.12	-0.80	0.05	0.02*
RH (%)	Dry	C OFF	10:00	62.95	62.96	2.37	-0.89	2.61	0.03*
			13:00	49.31	49.31	2.69	0.11	0.21	0.95
			15:00	41.13	40.98	3.05	0.37	-0.25	0.17
		C ON	10:00	69.37	69.75	2.66	-1.95	6.43	0.00*
			13:00	57.26	57.51	3.05	-0.79	1.45	0.10
			15:00	51.97	51.94	3.52	-0.12	-0.14	0.32
	Rainy	C OFF	10:00	76.98	77.01	2.12	-0.52	1.05	0.26
			13:00	63.42	63.37	2.25	0.11	-0.65	0.60
			15:00	62.09	61.96	2.65	0.74	0.74	0.10
		C ON	10:00	75.36	74.89	4.83	-1.06	5.00	0.00*
			13:00	66.92	65.88	5.53	0.46	0.62	0.05
			15:00	65.29	64.27	5.27	0.76	0.29	0.03*
W (m s^{-1})	Dry	C OFF	10:00	0.40	0.25	102.75	2.33	4.74	0.00*
			13:00	0.46	0.28	109.63	2.22	4.49	0.00*
			15:00	0.44	0.27	100.74	2.29	5.54	0.00*
		C ON	10:00	0.40	0.33	65.05	0.62	-0.38	0.00*
			13:00	0.44	0.35	65.52	1.28	1.35	0.00*
			15:00	0.48	0.41	71.93	1.25	1.25	0.00*
	Rainy	C OFF	10:00	0.22	0.16	74.91	2.14	4.58	0.00*
			13:00	0.13	0.13	23.21	0.05	-0.58	0.79
			15:00	0.18	0.14	64.90	1.86	3.75	0.00*
		C ON	10:00	0.66	0.62	79.35	0.75	-0.53	0.00*
			13:00	0.60	0.39	89.56	1.16	0.57	0.00*
			15:00	0.57	0.34	89.61	1.52	2.08	0.00*

C OFF - Coolers off; C ON - Coolers on; CV - Coefficient of variation; Cs - Coefficient of skewness; CK - Coefficient of kurtosis; W - Shapiro-Wilk normality test ($p \leq 0,05$); * Non-normal distribution

decreases during the rainy season due to the high moisture content in the air.

Similar to the temperature data, a low CV was observed, with 5.53 being the highest value. The mean and median were close to each other, and the data were normally distributed, which was confirmed by the normality test. Therefore, the data were found to be homogeneous, and the mean values are considered descriptively representative.

Further analysis of the results of descriptive statistics (Table 1), revealed that wind speed behaved differently from the other variables analyzed. It had a high CV (above 64% in most treatments) and a non-normal distribution, which was confirmed by the Shapiro-Wilk test and distinct mean and median values. This occurred due to the significant variability in the direction and magnitude of the natural and artificial winds, as the environment is influenced by the mechanical ventilation of the evaporative coolers and natural ventilation provided by the meshed gates installed on three out of four sides of the selection and packaging area of the packing house.

After analyzing the descriptive statistics of the variables T (temperature), RH (relative humidity), and W (wind speed), a geostatistical analysis was conducted. The results are listed in Table 2.

The exponential model proved to be most suitable for the spatial characteristics of the variables T (temperature) and UR (relative humidity). For the variable V (wind speed), the spherical and Gaussian models were the best-fit. The nugget effect ranged from 0.002 to 0.057 for variable T, from 0.057 to 1.511 for UR, and from 0.0001 to 0.032 for V. The closer the values of the nugget effect approach zero, the more accurate the estimates from kriging become, corroborating Vieira (2000), who explains that the lower the random variation, the more accurate the estimate becomes.

According to Ferraz et al. (2017a) and Rodrigues et al. (2023), the nugget effect is an important parameter of the semi variogram that occurs when the distribution of variables is unexplained or when the smallest distance between sample points is greater than the spatial dependence distance, considering the distance used in data sampling.

As it is not possible to quantify the individual contribution of the nugget effect, the literature suggests the use of certain indices to study this effect, such as the one proposed by

Table 2. Models and semi variogram parameters for temperature (T), relative humidity (RH), and wind speed (W) in the selection and packaging area of the packing house during dry and rainy seasons, with evaporative coolers switched on and off

Variable	Period	Treatment	Time	Model	Co	Co + C	a (m)	R^2	SQR	SDD	Class
T (°C)	Dry	C OFF	10:00	Exponential	0.026	0.055	5.79	0.529	0.000	0.52	Moderate
			13:00	Exponential	0.015	0.070	4.41	0.791	0.000	0.79	Strong
			15:00	Gaussian	0.022	0.049	12.89	0.979	0.000	0.55	Moderate
		C ON	10:00	Gaussian	0.026	0.061	11.03	0.956	0.000	0.57	Moderate
			13:00	Gaussian	0.057	0.125	10.48	0.921	0.000	0.55	Moderate
			15:00	Exponential	0.015	0.053	4.79	0.489	0.000	0.72	Moderate
	Rainy	C OFF	10:00	Exponential	0.020	0.041	2.64	0.203	0.000	0.51	Moderate
			13:00	Exponential	0.007	0.056	4.35	0.735	0.000	0.88	Strong
			15:00	Exponential	0.015	0.026	5.15	0.425	0.000	0.41	Moderate
		C ON	10:00	Exponential	0.002	0.034	3.39	0.649	0.000	0.94	Strong
			13:00	Exponential	0.012	0.092	3.78	0.77	0.000	0.87	Strong
			15:00	Exponential	0.002	0.054	3.75	0.805	0.000	0.96	Strong
RH (%)	Dry	C OFF	10:00	Spherical	0.057	1.560	1.65	0.129	0.242	0.96	Strong
			13:00	Exponential	0.308	1.837	2.28	0.13	0.642	0.84	Strong
			15:00	Gaussian	0.345	1.656	1.89	0.246	0.516	0.79	Strong
		C ON	10:00	Exponential	0.911	1.823	6.72	0.658	0.106	0.50	Moderate
			13:00	Exponential	0.535	3.272	3.47	0.454	0.674	0.84	Strong
			15:00	Exponential	1.511	3.057	9.63	0.726	0.300	0.51	Moderate
	Rainy	C OFF	10:00	Exponential	0.444	2.372	5.07	0.742	0.262	0.81	Strong
			13:00	Exponential	0.181	1.933	1.23	0.023	0.416	0.91	Strong
			15:00	Exponential	0.304	2.038	2.13	0.129	0.577	0.85	Strong
		C ON	10:00	Gaussian	0.503	2.981	1.70	0.257	1.130	0.83	Strong
			13:00	Exponential	0.600	4.142	2.88	0.322	1.990	0.86	Strong
			15:00	Exponential	0.620	3.963	3.96	0.444	1.890	0.84	Strong
W (m s^{-1})	Dry	C OFF	10:00	Gaussian	0.032	0.258	6.77	0.917	0.003	0.88	Strong
			13:00	Spherical	0.0001	0.307	6.71	0.880	0.006	1.00	Strong
			15:00	Spherical	0.001	0.244	5.51	0.852	0.004	1.00	Strong
		C ON	10:00	Gaussian	0.003	0.087	6.82	0.669	0.002	0.97	Strong
			13:00	Spherical	0.0001	0.086	8.46	0.752	0.001	1.00	Strong
			15:00	Spherical	0.0001	0.125	9.05	0.714	0.004	1.00	Strong
	Rainy	C OFF	10:00	Spherical	0.001	0.033	5.22	0.693	0.000	0.98	Strong
			13:00	Spherical	0.0001	0.001	5.16	0.92	0.000	0.94	Strong
			15:00	Gaussian	0.0003	0.020	8.95	0.932	0.000	0.99	Strong
		C ON	10:00	Gaussian	0.006	0.086	4.00	0.936	0.000	0.94	Strong
			13:00	Spherical	0.008	0.154	4.46	0.595	0.005	0.95	Strong
			15:00	Gaussian	0.017	0.134	2.34	0.663	0.001	0.87	Strong

C OFF - Coolers off; C ON - Coolers on; Co - Nugget effect; Co + C - Sill; a - Range; R^2 - Coefficient of determination; Sum of square of residuals (SQR); Spatial dependence degree (SDD); Class - interpretation of SDD

Cambardella et al. (1994). According to this classification, the degree of spatial dependence ranged from moderate to strong, indicating that the distribution of variables in space was not random.

To determine the limit of spatial dependence in semi variograms, the values of the range (a) are analyzed, which indicate how much the variable is influenced by space (Ferraz et al., 2017b). In this work, the range varied from 2.64 to 12.89 m for temperature, 1.23 to 9.63 m for RH, and 1.25 to 11.48 m for W (Table 2). This suggests that the horizontal distance of the sample mesh could vary between 1.23 and 12.89 m to obtain the same precision as the sample data, meaning that the 3.5 m distance used was appropriate.

Figure 2 shows the kriging maps of air temperature for the dry (D) and rainy (R) periods, for treatments without a cooling unit (C OFF) and with a cooling unit (C ON) at 10:00, 13:00 and 15:00 h.

Epstein & Moran (2006) consider that the range of environmental thermal comfort is between 20 and 27 °C. However, as agricultural workers in the north-eastern semi-arid region are adapted to the hot and dry climate, they experience cold discomfort and increased susceptibility to disease when the ambient temperature varies between 20 and 25 °C (Miranda et al., 2025). Therefore, for local conditions, the temperature range between 25 and 27 °C can be considered ideal for thermal comfort.

When looking at Figure 2, it is noticeable that the air temperature is only in the thermal comfort zone only at 10:00 h, except for the C OFF treatment during the rainy season. It is also noticeable that in the rainy season, when the cooling units are switched on, the right region of the map is outside the thermal comfort zone, with temperatures above the ideal.

In the C ON treatment, there was greater spatial variability in temperature, with higher values in the right-hand region of the maps (beginning of the processing line). As the coolers are positioned closer to the middle and end of the processing line (left-hand region of the maps), temperatures were lower in these areas. Zhou & Ooka (2020) state that the air movement within the facility influences the isothermal distribution.

When the cooling units were switched on, there was a significant reduction in temperature, although still outside the

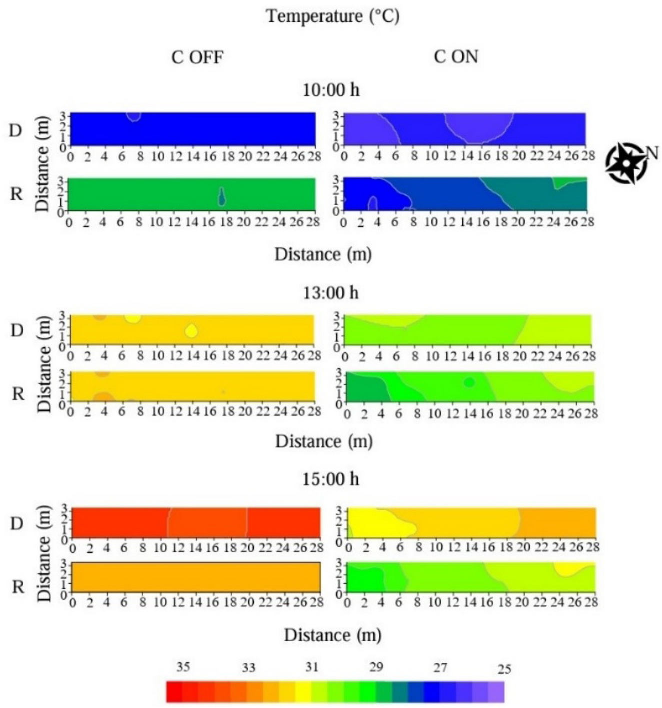

Figure 2. Spatial variability of air temperature in the selection and packaging area of the packing house during dry (D) and rainy (R) periods, and treatments without cooler (C OFF) and with cooler (C ON)

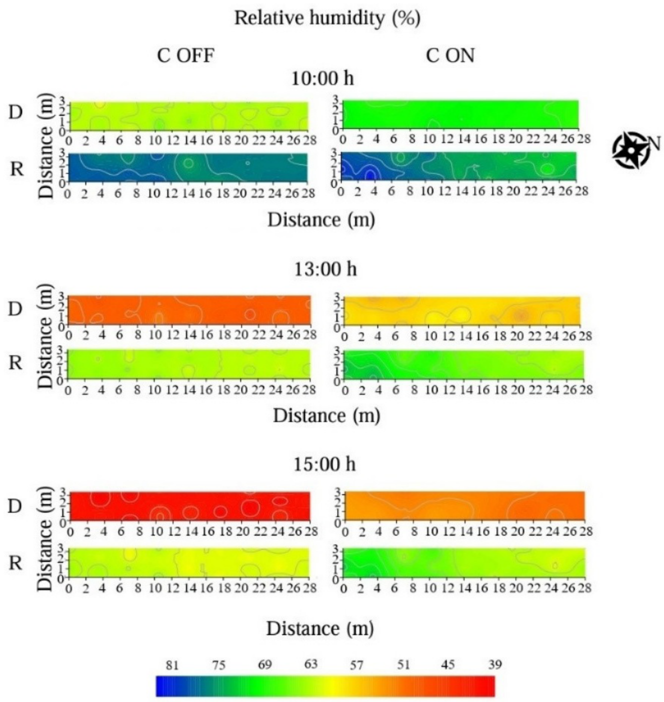

Figure 3. Spatial variability of relative humidity in the selection and packaging area of the packing house during dry (D) and rainy (R) seasons and treatments without cooler (C OFF) and with cooler (C ON)

thermal comfort range, and with heterogeneous distribution. Faria et al. (2008), working with non-climatized and climatized sheds, observed that misting in the shed increased the spatial variability of microclimatic attributes.

Due to the traceability process of the packed fruits, employees work at fixed workstations throughout the harvest season, without rotation of positions. Those who work at workstations near the evaporative coolers work in better conditions and may have higher productivity. It was also observed that individuals working in the region further away from the evaporative coolers took more hydration breaks.

The environment showed less spatial variability in relative humidity (Figure 3), with the exception of the C ON treatment at 10:00 h in the rainy season, where higher values were observed in the left region of the map, near one of the evaporative coolers.

The spatial distribution of wind speed can be seen in Figure 4. There was spatial variability both in the dry and rainy seasons, with evaporative coolers on and off, with higher values in the central and left regions. These areas are directly influenced by evaporative coolers and screened gates that facilitate air circulation.

The uniformity of climatic parameters is essential for the quality of the thermal environment (Khovalyg et al., 2020). Curi et al. (2014) state that knowledge of the spatial variability of environmental attributes and the creation of kriging maps can assist in the proper management of ventilation systems. Thus, the need to adjust the thermal environment in the selection and packaging area of the packing house, where the beginning of the processing line has critical control points becomes apparent.

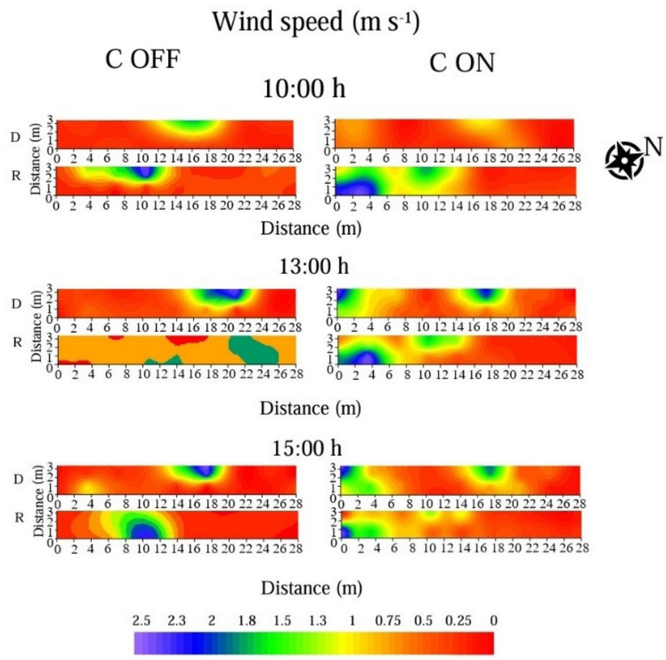

Figure 4. Spatial variability of wind speed in the selection and packaging area of the packing house during dry (D) and rainy (R) seasons, and treatments without cooler (C OFF) and with cooler (C ON)

It is advisable to install fans and distribute them so that they can direct the flow of cooler and more humid air from the evaporative coolers to the region furthest away from them (right zone in the maps). In this way, it would be possible to homogenize the environment without increasing the relative humidity and provide create conditions for workers to avoid thermal stress, and thus increase everyone's productivity.

Conclusions

1. The evaporative cooling system provided better thermal conditions in the selection and packaging area of the packing house but did not homogenize the environment.

2. Critical control points were identified at the beginning of the processing line, the area furthest away from the evaporative coolers

3. The use of geostatistics and the creation of kriging maps enabled the definition of areas with different spatial variability for climatic attributes, allowing specific problem regions to be identified.

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