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Bioclimatic performance of wet coffee processing facilities: conditions for workers and coffee

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Desempeño bioclimático de instalaciones de procesamiento de café húmedo: condiciones para los trabajadores y el café

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ABSTRACT

Keywords:
Computational simulation
Hygrothermal behavior
Post-harvest coffee
Thermal comfort
WBGT index.

This study aimed to evaluate the bioclimatic performance of three wet coffee processing facilities in Colombia, focused on the conditions for workers and coffee parchment, through computer simulation. In addition to temperature and relative humidity, the Wet-Bulb Globe Temperature index (WBGT) was simulated during the highest coffee production month. The proposed simulation model was able to predict hygrothermal behavior within the three coffee processing facilities. Case 3 presented the warmest environment, and case 2 the most humid environment concerning the appropriate conditions for the coffee and the worker. The WBGT index limit was exceeded in case 3. Since this type of facility emits large amounts of heat and steam, constructive modifications are suggested to improve the environmental conditions of workers and coffee. Mainly, the physical separation of the heat exchangers is recommended, which ideally should be outside the post-harvest facility. The steam produced in the drying process should be quickly evacuated with ventilation strategies. Additionally, the use of strategies that reduce the energy gain from solar radiation is suggested.

RESUMEN

Palabras clave:
Simulación computacional
Ambiente higrotérmico
Poscosecha de café
Confort térmico
Índice WBGT

Este estudio tuvo como objetivo evaluar el desempeño bioclimático de tres instalaciones de procesamiento húmedo de café en Colombia, enfocado en las condiciones para los trabajadores y el café pergamino, a través de simulación computacional. Además de la temperatura y la humedad relativa, se simuló el índice de temperatura del globo negro y bulbo húmedo (WBGT) durante el mes de mayor producción de café. El modelo de simulación propuesto pudo predecir el comportamiento higrotérmico dentro de las tres instalaciones de procesamiento de café. El caso 3 presentó el ambiente más cálido, y el caso 2 el ambiente más húmedo con respecto a las condiciones adecuadas para el café y el trabajador. En el caso 3 se superó el límite del índice WBGT. Dado que este tipo de instalaciones emite grandes cantidades de calor y vapor, se sugieren modificaciones constructivas para mejorar las condiciones ambientales de los trabajadores y el café. Principalmente, se recomienda la separación física de los intercambiadores de calor, que idealmente deberían estar fuera de la instalación de poscosecha. El vapor producido en el secado debe evacuarse rápidamente con estrategias de ventilación. Además, se sugiere el uso de estrategias que reduzcan la ganancia de energía de radiación solar.

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In Colombia, coffee is mainly processed wet, through sub-processes that include pulping, fermentation, washing, and drying of the beans. The bioclimatic conditions of the facilities where these processes take place can be decisive for both the comfort of the workers (Guerra-García *et al*., 2019) and the quality preservation of dry parchment coffee. The coffee is often stored there for a long time (sometimes exceeding two weeks), where a large amount of heat and steam is generated by the machines during mechanical drying (Osorio *et al*., 2018; Osorio *et al*., 2020).

On the one hand, according to Todd and Valleron (2015), the heat generated by humans increases with increasing physical activity. Roscani *et al*. (2017) and Gutiérrez *et al*. (2018) stated that the combination of this situation with a stressful thermal environment can result in considerable occupational hazards. Workers in the wet coffee process develop physically demanding activities, in a hot and humid environment, which can generate heat stress, weakness in the general state of health, alterations in psychosensory reactions, and decreased productivity (Roscani *et al*. 2017; ISTAS-C, 2017; Gutiérrez *et al*. 2018).

For the evaluation of workers' hygrothermal environment, the Ministry of Labor and Social Security of Colombia proposes that the appropriate temperature range should be between 14 and 25°C, and the relative humidity between 30 and 70%. For a more complete comfort analysis, the use of comfort indices is required.

To evaluate human performance in work under conditions of exposure to heat, different standards have defined the use of the Wet Bulb Index and Globe Thermometer (WBGT). Among them, Resolution 2400 of 1979 establishes some provisions on housing, hygiene, and safety in the workplace in Colombia (MTSS, 1979), the international standard ISO 7243, (1982) estimates the heat stress of workers, as well as the Brazilian regulatory standard - NR 15, attachment n. 3 (ABNT-NBR, 2011). These last two standards also establish the lines for calculating the WBGT index, in addition to proposing its limits.

The WBGT index is an indicator of thermal comfort that considers air temperature, metabolism, radiant heat, air velocity, and relative humidity as the main drivers of thermal overload (MTSS, 1979; ISO 7243, 1982; ABNT-NBR, 2011; Roscani *et al*. 2017). Guerra-García *et al*. (2019) used this index for comfort analysis in coffee post-harvest facilities in Colombia, obtaining satisfactory results.

On the other hand, the quality of dry parchment coffee can be compromised during storage due to the hygrothermal conditions of the environment. According to Puerta (2016), The quality of dry parchment coffee stored in Colombia, with humidity between 10 and 12% in the bean, can be preserved for a maximum of six months, with an air temperature below 20 °C and relative humidity between 60 and 70%. Different environmental conditions ultimately affect the taste and quality of the coffee drink.

Studies on the bioclimatic performance of facilities for wet coffee processing are few. The available literature suggests that these buildings present unsuitable storage environments that can affect the quality of the coffee (Osorio *et al*., 2020). Additionally, there is very little research that evaluates the thermal comfort of workers within post-harvest facilities (Guerra-García *et al*., 2019). According to Herrera *et al*. (2015), this is a widespread problem in the food industry, mainly in Latin America and the Caribbean.

Computational simulation has become a useful tool for the design and bioclimatic evaluation of buildings since it allows the analysis of mass and energy transfer phenomena, internal loads, occupancy patterns, transitory analysis, among others (Al-Saadi and Al-Jabri, 2020). However, in the evaluation of the built environment, the computational simulation models must be validated with experimental data to obtain reliable results.

One of the most internationally recognized bioclimatic and energy simulation software for buildings is EnergyPlus™. This open-source software, developed by the US Department of Energy (DoE), is capable of simulating long periods of time with the help of local weather files. The EnergyPlus™ program is a collection of many program modules that work together to calculate the energy required for air conditioning of buildings using 3D geometries, climate files, internal loads (machines and metabolism), usage patterns, thermal properties of materials, among others (DoE, 2019).

The EnergyPlus™ software allows generating computational models to evaluate the bioclimatic performance of coffee post-harvest facilities (Osorio *et al.*, 2018), seeking solutions that benefit both the conservation of parchment coffee and the thermal comfort of the worker (Guerra-García *et al.*, 2019). This study aimed to evaluate the bioclimatic performance of three wet coffee processing plants in Colombia, focused on the comfort conditions of the workers and the environmental conditions for the conservation of parchment coffee.

MATERIALS AND METHODS

Three case studies corresponding to three wet coffee processing facilities were compared, which from now on will be called case 1, 2, and 3. Except for their architecture, the three cases have similar geographic location conditions (municipalities of the north region of Antioquia - Colombia), mechanical drying, annual production of 30 t of dry parchment coffee, and peak production in November. Table 1 summarizes the description of the location and architectural details of the three case studies.

Data of air temperature and relative humidity inside the three study cases were collected employing an Extech Instruments datalogger of the RHT20 brand, using a temperature measurement interval between -40 and 70 °C with a resolution of 0.1 °C, as well as a range between 0 and 100% relative humidity, with a resolution of 0.1. The collections were carried out every 5 min during three continuous days in each case, in November 2016, by fixing the equipment in the geometric center of each installation.

Table 1. Description of location and architectural details of the case studies.

Item	Case 1	Case 2	Case 3
Location: coordinates, altitude and municipality.	6°24'47,64''N, 75°20'47,08''W, 1508 masl, Barbosa.	6°21'42,16''N, 75°34'44,83''W, 1698 masl, Bello.	6°29'22,79''N, 75°00'41,86''W, 1435 masl, San Roque.
Architectural configuration	Flat construction. Chimney over the drying area, cherry coffee receipt dry hopper on the slab.	Two-level flat construction. Wet process and coffee drying process on the first level, cherry coffee receipt dry hopper, and housing on the second level. Annex buildings.	Staggered construction. Wet and dry process on different levels, cherry coffee receipt dry hopper on the fourth level.
Buildings dimensions	Width: 6.0 m Length: 11.0 m Height: 3.50 m	Width: 9.10 m Length: 10.05 m Height: 3.60 and 3.80 m	Width: 5.10 m Length: 14.50 m Height: 2.40, 1.90 and 2.45 m
Wall materials	Exposed perforated brick	Brick plastered up to a height of 2.0 m, exposed to the roof.	Brick wall, ceramic cladding.
Roof materials	Slab lightened with bricks	Slab lightened with bricks in the first part, and fiber cement tile in the second part.	Slab lightened with bricks on the upper level, and aluminum tile on the lower levels.
Floor materials	Exposed concrete	Exposed concrete	Ceramic coated concrete.
Openings	Openwork brick to finish all the walls at the top.	Three doors and six openings with security bars.	Grille door in the first and last levels, window in the first level and openings with security grilles between slopes.

The computational simulation analysis was carried out in the EnergyPlus™ program, based on the weather file of the city of Medellín, due to its availability, proximity (linear distance from Medellín to Bello 12 km, Barbosa 34 km, and San Roque 65km), and a similar climate to the location zones of the facilities under study (DesignBuilder, 2017). For the simulation model, a 3D geometry of each case study was elaborated in the Sketchup® software. With the help of the OpenStudio plugin, thermal zones were created. Finally, files with an idf extension were generated for each case (Figure 1).

The thermal properties of construction materials such as density, thermal conductivity, and specific heat were obtained from the ABNT-NBR 15220-2 (2005). To simplify the 3D model in case 1, the areas with openwork brick were assumed as windows, adding sun protection to simulate interference with light (Osorio *et al*., 2016). The mass of the material composed of brick and concrete, constituted by stairs, hydraulic classifier, and fermentation tanks was quantified and added to the immediate wall, to consider the effect of thermal inertia in the three cases.

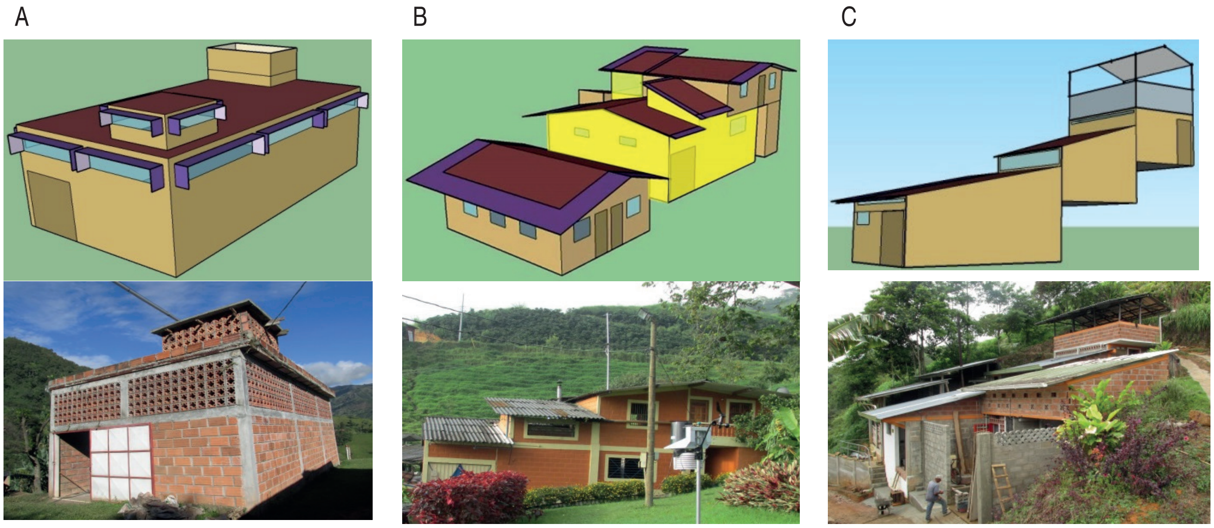

Figure 1. 3D geometries of the three case studies: A case 1, B case 2 (yellow area), and C case 3.

For the calculation of the energy balances (Equation 1), the internal loads were considered: powers of the coffee processing equipment (pulping machines and mechanical drying), and the luminaires (Table 2). Likewise, the heat generated from the human metabolism was considered as 440 kcal h^{-1} (512 W), corresponding to an intermittent work of lifting, pushing, or dragging weights (ABNT-NBR, 2011).

$$\frac{C_z dT_z}{dt} = \sum_{i=1}^{n} \dot{Q}_i + \sum_{i=1}^{n} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{n} \dot{m}_1 C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \tag{1}$$

where,

$\sum_{i=1}^{n} \dot{Q}_i$: Sum of internal convective loads (w);

$\sum_{i=1}^{n} h_i A_i (T_{si} - T_z)$: Convective heat transfers from area surfaces (w);

$\dot{m}_{inf} C_p (T_\infty - T_z)$: Heat transferred through the grooves (w);

$\sum_{i=1}^{n} \dot{m}_i C_p (T_{zi} - T_z)$: Heat transfer due to interzone air mixing (w);

$\dot{Q}_{sys}$: Air systems outlet (w);

$\frac{C_z dT_z}{dt}$:Stored energy (w);

C_z : $\rho_{air} C_p C_s$

ρ_{air} : Zone air density (kg m^{-3});

C_p: Specific heat of the air (J kg^{-1} $°K^{-1}$);

C_s: Sensible heat capacity multiplier (J kg^{-1} $°K^{-1}$).

Table 2. Power of machines for wet processing of coffee.

Equipment	Power	Usage patterns (h)
Pulping module	3357.0 W	11:00 - 12:00 and 17:00 - 18:00
Engine of fan of mechanical dryer	2238.0 W	6:00 - 19:00
Submersible pump *	746.0 W	16:00 - 16:30
Heat exchanger of mechanical dryer case 1	127570.6 W	6:00 - 18:00
Heat exchanger of mechanical dryer case 2	57381.8 W	6:00 - 18:00
Heat exchanger of mechanical dryer case 3	156053.3 W	6:00 - 18:00
Luminaires	10 W m^{-2}	17:00 - 20:00

* Only present in case 3

The simulation was carried out for the entire month of November in each case, from hour to hour, to determine the bioclimatic performance of the facilities during the peak period of coffee production, specifically for analyzing the conditions for the workers and parchment coffee. Table 3 shows the schedules used for the computational simulation in EnergyPlus™.

For the validation of the computational model, the experimental data (720 data) of temperature and relative humidity of the air was used to calculate the Normal Mean Square Error (NMSE) (ASTM, 2002) (Equation 2). NMSE values less than 0.25 are considered acceptable and good indicators of concordance. The agreement between the experimental values and the simulated values increases as the value is closer to zero.

Table 3. Schedules used for the computational simulation.

Hours	Activities
6:00:00	Fuel feed for drying coffee
8:00:00	Breakfast
9:00:00	Washing of parchment coffee
10:00:00	Hydraulic classification of coffee
11:00:00	Pulping
12:00:00	Lowering the coffee layer inside the three-layer dryer
13:00:00	Lunch
14:00:00	Fuel feed for drying coffee
15:00:00	Washing of parchment coffee
16:00:00	Hydraulic classification of coffee
17:00:00	Pulping
18:00:00	Lowering the coffee layer inside the three-layer dryer
19:00:00	Packing of parchment coffee

$$NMSE = \frac{1}{n}\sum_{i=1}^{n}\frac{(Y_{pi} - Y_{mi})^2}{Y_{pi}Y_{mi}} \qquad (2)$$

where Y_{pi} is the predicted value, Y_{mi} is the measured value, and n is the number of data.

Equation 3 was used to analyze the WBGT index in the three case studies from the simulations. It is suitable for the evaluation of internal environments (without solar load), according to NR 15, annex n. 3 (ABNT-NBR, 2011).

$$WBGT=0.7T_W+0.3T_g \qquad (3)$$