Sustainable Natural Solar Drying of Microbreweries Spent Grains: A Comparison with Common Electric Convective Drying

MP Fabani¹, JP Capossio², A Reyes-Urrutia³, R Rodriguez³, and G Mazza².

1 Biotechnology Institute, Faculty of Engineering, National University of San Juan. 1109 Av. Libertador San Martín (O) St., J5400ARL, San Juan, Argentina.
2 Institute for Research and Development in Process Engineering, Biotechnology and Alternative Energies, (PROBIEN, CONICET – National University of Comahue), 1400 Buenos Aires St., 8300, Neuquén, Argentina
3 Chemical Engineering Institute, Faculty of Engineering, National University of San Juan. Research Group associated with PROBIEN Institute. 1109 Av. Libertador San Martín (O) St., J5400ARL, San Juan, Argentina.
E-mail: german.mazza@probien.gob.ar

Abstract. In recent years, local microbreweries are increasingly capturing the consumer’s interest with a wide range of different types of beer. Because of the insertion of microbreweries scattered around the country, large amounts of spent grains have been made available locally to be used, for instance, as animal feed. However, those spent grains, which are mainly formed by malting barley (or malt), are materials suitable for further valorization. Turning the spent grains from waste to a raw material that can be later used to produce non-traditional flour requires a thermal treatment, i.e. a drying process. A natural convection solar dryer (NCSD) was evaluated as an alternative to a conventional convective electric drying system for the dehydration process of local microbrewer’s spent grains. Two types of breweries’ spent grains -BSG- (Golden Ale and Red Ale) were dried at different daytime hours. Sustainability indexes, Specific Energy Consumption (SEC), and CO₂ emissions of the conventional dryer were calculated and used to determine the environmental benefits and drawbacks of the NCSD.

Keywords: natural convection solar dryer, electric convective dryer, brewer’s spent grains, waste valorization.

1. Introduction

The beer production market worldwide is and has been a highly concentrated one, with a considerable market share controlled by a few major brewing companies which produce the most popular industrial lager type beer. However, since a decade or so ago, local microbreweries are steadily growing and offer the consumer a wide range of different types of beer. The Argentinian beer production market does not escape this reality and the craft beer industry is experiencing a 30% annual growth (pre-pandemic) [1]. Beer is one of the most popular and consumed alcoholic beverages in the world, and particularly in Argentina, its consumption began to increase significantly, reaching 20 million hectoliters per year [2]. Beer is an alcoholic beverage made from sugars obtained from cereals and other grains (mainly barley and wheat), flavored and aromatized with hops (among other herbs and additives), which are then fermented in water with yeasts of the Saccharomyces genus. In the process described above, large quantities of a solid fraction residue are produced, called brewer’s spent grain (BSG) [3], which
constitutes the most abundant byproduct of the beer brewing procedure, representing 85% of the process residues and representing on average 31% of the original weight of the malt used during the process [4, 5].

The final disposal of this residue generates a serious environmental problem for breweries, considering that the volume of beer bagasse generated is approximately 600 g per liter of beer brewed. Moreover, the creation of dozens of microbreweries all around the country has made large amounts of spent grains available locally. BSG is mainly used as animal feed and in a low percentage in the production of biogas or eliminated in waste disposal sites (landfills) [6]. However, those spent grains (by-products) have multiple applications due to their low cost, year-round availability, and valuable chemical composition. The BSG chemical composition is influenced by different factors such as grain used (barley, rice, wheat, corn), harvesting time, processing method, and brewing conditions e.g. recipe [7]. Bagasse is mainly composed of 15-26% protein and 70% fibers. Fibers are in the form of cellulose (16-25%), hemicellulose (28-35%), and lignin (7-28%) [5]. In this context, Bolwig et al. [6] and Kavalopoulos et al. [8] studied the valorization pathways of BSG towards animal feed and biofuels production, respectively under the circular bio-economy and biorefinery concept. Moreover, BSG are materials suitable for further valorization through a byproduct development process such as non-traditional flour [9]. BSG were used as an ingredient to enhance the fiber contents in recipes such as pasta [10], pieces of bread, and snacks [3, 11, 12]. Recently, the prospective utilization of BSG for energy and food in Africa and its global warming potential were studied by Maqhuzu et al. [13].

In order to transform the BSG from waste to raw material, it is necessary to dry it, due is its high initial moisture (60-80%). This makes it vulnerable to fast deterioration and spoilage within a few hours after production [14] and one ton of BSG in a waste disposal site discharges 513 kg of CO₂ equivalent of greenhouse gases [8]. Currently, several alternatives are used for food dehydra, including hot air oven drying and the natural convection solar dryer (NCSD) [15, 16]. This latest technology (NCSD) is reliable, economic, and environmentally friendly, has lower operational costs than conventional electrical systems, and is more efficient than direct sun drying [15, 16]. Moreover, solar drying generates a reduction in CO₂ emissions [17].

The working principle of natural convection solar dryer (NCSD) relies upon air being heated in the dryer by solar heat: the air relative humidity will decrease and air will naturally flow toward the dryer exhaust. This air will remove moisture from the product and will be released into the atmosphere.

The authors’ literature search showed that there is little information on BSG drying. Mallen and Najdanovic-Visak [18] studied drying kinetics of BSG at four temperatures (60, 70, 80 and 90 °C) to produce biodiesel from them, while Kavalopoulos et al. [8] dehydrated and simultaneously milled BSG by a rotary drum food waste dryer at 105 °C, to subsequently produce biodiesel, bioethanol and/or biogas.

**Objectives of this work**

The main objective of this work was to evaluate a natural convection solar dryer (NCSD) as an alternative to a conventional convective electric drying system for the dehydration process of local microbrewer’s spent grains. Two types of brewer spent grains Golden Ale (BSG-GA) and Red Ale (BSG-RA) were dried at different daytime hours in an NCSD. Moreover, the BSG were dehydrated in a conventional convective electric dryer (CCED) at 60, 65, 70, 75, 80, 85, 90, and 95 °C. Kinetics was studied for both drying systems. The obtained dimensionless moisture ratio values (MR) were modeled using eleven semi-theoretical drying and empirical models. To perform the aim above mentioned, sustainability indexes, Specific Energy Consumption (SEC), and CO₂ emissions of the conventional dryer were calculated and used to assess the environmental benefits and drawbacks of the NCSD.

**2. Materials and Methods**

**2.1. Samples**

The brewers’ spent grains (BSG) from the production of Golden Ale (BSG-GA) and Red Ale (BSG-RA) beer were used (Figure 1). The BSG were gathered after being removed from the maceration process in the establishment “Cerveceria Cumbre”, Province of San Juan, Argentina. All samples were stored at 4 °C in the dark until analysis/drying within 1-2 days after sampling.
2.2. Analysis
The moisture, pH, and titratable acidity (% citric acid) were analyzed in collected brewers’ spent grains (raw and dried BSG) following the methodology of AOAC (Official Methods of Analysis, 2010). All analyses were realized in fresh and dried BSG and carried out three times (n=3). The data were expressed as means ± standard deviation.

2.3. Drying equipment and experimental procedure

2.3.1. Conventional Convective Electric Dryer (CCED)
The convective drying experiments of BSG, without any pretreatment, were performed at eight temperatures: 60, 65, 70, 75, 80, 85, 90, and 95 °C, in an oven, described previously by Baldan et al. [19], maintaining the air velocity constant at 1 m/s in the course of all drying trials and measuring the average weight loss, reported with an average value ≪ 5%.

2.3.2. Natural Convection Solar Dryer (NCSD)
The solar drying process was carried out in a solar dehydrator with natural airflow (Figure 2) until the moisture content was lower than 10%. BSG were placed on grid trays inside the solar dryer. In each tray the thickness of the BSG layer was of 5±0.5 mm. The trays were loaded with the same amount of BSG. So each tray's load was previously weighted with a laboratory balance. Then the BSG were placed on top of it and evenly spread across the tray with a special ruler to ensure a uniform thickness layer. The drying trials were carried out on two different days (14 and 15 of December 2020) and each by triplicate (3 trays per trial), in the Albardón Department, San Juan Province, Argentina. Ambient temperature was measured with an indoor-outdoor thermometer with hygrometer clock (Gralf TGF-298), while the solar irradiance was recorded with a solar power meter (TENMARS TM-206). In turn, they were started at two different times (8.30 a.m. and 11 a.m.), in order to analyze the influence of ambient temperature and humidity on the drying of the samples. Weight loss data were taken as a function of time, during the drying process until a constant weight was reached. The final moisture of samples was determined at 105 °C in a Radwag PMR50 analyzer [20]. The dried samples were stored in the dark at room temperature (~20 °C) until analysis, within 2 weeks after sampling. All analyses were carried out in triplicates and the data were expressed as means ± standard deviation.
2.4. Mathematical modeling of drying curves

MR was determined employing the experimental data obtained at each time interval [21]. The experimental drying curves of BSG (MR vs t) were constructed and a set of 11 different empirical models from the literature were used [22]. To evaluate the fit of the mathematical models with the experimental data, the statistical coefficients: chi-squared ($\chi^2$), the sum of squared errors (SSE) and root mean squared errors (RMSE) were used. The best fits are for those models with the lowest values of $\chi^2$, SSE and RMSE and the highest values of $R^2$.

2.5. Specific energy consumption and CO2 emissions

The total energy needed to dry 1 kg of fresh BSG was calculated according to the following equation (1) [23].

$$SEC = (c_{pa} + c_{pv} \cdot h_a) \cdot q \cdot t \cdot \frac{(T_{in} - T_{am})}{m_v \cdot V_h}$$  (1)

In Argentina, the electric energy feed for the conventional dryer is provided by a mixture of renewable and non-renewable sources (wind, hydro and natural gas thermal power station, among others). According to Climate Transparency 2019 [24], the electricity CO2 emission factor for Argentina is 0.3583 kg CO2/kWh. So, to obtain the CO2 emissions when 1 kg of BSG is dried, the SEC must be multiplied by this constant.

3. Results

3.1. Moisture, pH, and titratable acidity in BSG: fresh and dried

The initial average moisture of the BSGs fresh was high, with values of 64.3±0.2% for BSG-GA and 74.2±0.5% for BCG-RA, which is within the informed range, from 60 to 90 mass % [18]. Subsequently, the pH of the fresh bagasse was analyzed, which was 5.63±0.08 for BSG-GA and 6.06±0.05 for BSG-RA, while the titratable acidity values expressed in % citric acid was 0.40±0.02 and 0.37±0.02%, respectively.

The BSG dried in the CCED presented a moisture content of less than 7%. The pH and acidity values vary according to the drying temperature, being in the range between 5.4 -5.8 and from 0.65 to 1.10%, respectively.
The moisture content of BSGs solar-dried was less than 6-7%, pH was 5.49±0.06 for BSG-GA, and 5.62±0.02 for BSG-RA, while the titratable acidity values expressed in % citric acid were 0.56±0.05 and 0.52±0.01 %, respectively.

3.2. Drying characteristics of BSG

The drying curves of BSG-GA and BSG-RA in the CCED and NCSD were calculated. The results in the CCED showed that drying curves followed an exponential decay. A first phase, where the moisture is lost rapidly, presenting high drying rates, and a second phase resulted in low drying rates and occurred until the BSGs reached the minor moisture. The drying rate increased with the temperature because of the increasing heat transfer potential between the air and the BSG, favoring the BSG water evaporation. The models that best fitted the experimental data, taking into account the statistical tests applied, were: Midilli (SSE=0.000041; RMSE=0.0062, and $\chi^2=0.000043$), followed by the Two-term model (SSE=0.000066; RMSE=0.0079, and $\chi^2=0.000069$). Therefore, it is recommended to use this model to predict the variation of RM over time for both BSG for the tested temperature range (60-95 °C).

In the NCSD it was observed that greater efficiency of the device was achieved by starting the BSG drying process at 11 a.m., accomplishing a decrease in moisture content in a shorter time, for the two varieties of BSG studied. Starting the trial at 11 a.m., the drying time to achieve a product with less than 10% was reduced from 430 to 390 min for BSG-RA and from 420 to 345 min for BSG-GA. When applying mathematical modelling to the data, the Midilli model (SSE=0.000026; RMSE=0.0158, and $\chi^2=0.000042$), followed by the modified Henderson and Pabis model (SSE=0.000034; RMSE=0.0181, and $\chi^2=0.000084$), were the best fit to the experimental data, with the Midilli model having the highest $R^2$ value.

3.3. Comparative analysis of the conventional and solar drying processes

Tables 1 and 2 show the results of the conventional convective drying process of the raw matter. The BSG of both varieties was dried at eight different temperatures, ranging from 60 °C to 95 °C. As expected, there are no significant differences from the environmental impact indicators’ point of view. Both ales show similar values for SEC and CO$_2$ emissions, averaging 346.92 kWh/kg and 124.3 kg CO$_2$/kWh for SEC and CO$_2$ emissions, respectively. The operational indicators also present similar values for both BSG, averaging 51.23 minutes of batch time and 0.86 USD of grid electricity per kilogram of raw material. From that perspective only, higher drying temperature values are more efficient.

Table 1. Results of the conventional convective drying process of the raw matter: Golden Ale

| Drying temperature (°C) | Batch time (min) | Total energy consumption (kWh) | Removed water (kg) | SEC (kWh/kg) | CO$_2$ emissions (kg CO$_2$/kWh) | Electricity cost (USD/kg) |
|------------------------|------------------|-------------------------------|--------------------|--------------|-------------------------------|-------------------------|
| 60                     | 85               | 0.29                          | 0.001684           | 410.73       | 147.16                        | 1.03                    |
| 65                     | 65               | 0.24                          | 0.001596           | 378.75       | 135.71                        | 0.95                    |
| 70                     | 54               | 0.21                          | 0.001613           | 350.25       | 125.50                        | 0.88                    |
| 75                     | 50               | 0.21                          | 0.001657           | 350.77       | 125.68                        | 0.88                    |
| 80                     | 44               | 0.20                          | 0.001726           | 325.97       | 116.80                        | 0.81                    |
| 85                     | 40               | 0.19                          | 0.001639           | 340.44       | 121.98                        | 0.85                    |
| 90                     | 36.5             | 0.19                          | 0.001680           | 328.33       | 117.64                        | 0.82                    |
| 95                     | 34               | 0.18                          | 0.001877           | 294.80       | 105.63                        | 0.74                    |
Table 2. Results of the conventional convective drying process of the raw matter: Red Ale

| Drying temperature (°C) | Batch time (min) | Total energy consumption (kWh) | Removed water (kg) | SEC (kWh/kg) | CO₂ emissions (kg CO₂/kWh) | Electricity cost (USD/kg) |
|------------------------|------------------|--------------------------------|-------------------|--------------|----------------------------|--------------------------|
| 60                     | 75               | 0.26                           | 0.00149           | 409.59       | 146.76                     | 1.02                     |
| 65                     | 68               | 0.25                           | 0.00180           | 351.32       | 125.88                     | 0.88                     |
| 70                     | 59               | 0.23                           | 0.00189           | 326.60       | 117.02                     | 0.82                     |
| 75                     | 55               | 0.23                           | 0.00194           | 329.56       | 118.08                     | 0.82                     |
| 80                     | 44.5             | 0.20                           | 0.00165           | 344.86       | 123.56                     | 0.86                     |
| 85                     | 41.8             | 0.20                           | 0.00169           | 345.02       | 123.62                     | 0.86                     |
| 90                     | 35.1             | 0.18                           | 0.00164           | 323.43       | 115.89                     | 0.81                     |
| 95                     | 32.83            | 0.18                           | 0.00157           | 340.31       | 121.93                     | 0.85                     |

Table 3 shows the solar dryer’s results of the drying process of the raw feedstock. Figure 3-A presents the corresponding drying curves. The experiments were carried out during the austral summer (which coincides with the boreal winter) at two different daytime hours, 8.30 and 11 a.m., for each BSGs. The ambient temperature and solar irradiance were recorded and reported in Figure 3-B.

| BSG         | Daytime hour | Batch time (min) | SEC (kWh/kg) | CO₂ emissions (kg CO₂/kWh) | Electricity cost (USD/kg) |
|-------------|--------------|------------------|--------------|----------------------------|---------------------------|
| Golden Ale  | 08:30        | 420              | 0.00         | 0.00                       | 0.00                      |
| Golden Ale  | 11:00        | 345              | 0.00         | 0.00                       | 0.00                      |
| Red Ale     | 08:30        | 430              | 0.00         | 0.00                       | 0.00                      |
| Red Ale     | 11:00        | 390              | 0.00         | 0.00                       | 0.00                      |

Figure 3. (A) Solar drying curves. (B) Ambient temperature and solar irradiance during drying (two consecutive sunny days in the austral summer, 14 and 15 December 2020)

Results showed an average batch time of 396 minutes, with the BSG-RA presenting slightly longer drying periods, due to the higher initial moisture content of the BSG-RA compared to the BSG-GA sample. Moreover, the NCSD have a zero operating costs because the sun is a freely available source of energy and there is no forced air flow. As a consequence, both environmental impact indicators have a
value of zero. Table 4 presents a summary of the most important process and environmental indicators previously explained.

|                          | Conventional convective electric dryer (CCED) | Natural convection solar dryer (NCSD) |
|--------------------------|---------------------------------------------|--------------------------------------|
| Average drying temperature (°C) | 77.5                                        | 46.5                                 |
| Average batch time (min)    | 51.23                                       | 396                                  |
| Average SEC (kWh/kg)       | 346.92                                      | 0                                    |
| Average CO₂ emissions (kg CO₂/kWh) | 124.3                                      | 0                                    |
| Average operating cost (USD/kg) | 0.86                                        | 0                                    |

4. Conclusions

From the environmental perspective, the NCSD eliminates 100% of the CO₂ emissions and requires no grid energy to operate, thus reducing the overall operating costs (if we include labor cost within the overall operating costs). The main identifiable drawback of the NCSD is that the batch times are significantly longer, thus reducing the yield at least in the scale of the dryer used in these experiments. Also, the NCSD produces a dried product with better quality characteristics, as indicated by the lower acidity values. Another important aspect to consider is the equipment costs. The solar dryer is about 40-45% cheaper than a conventional electrical dryer.

5. References

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Acknowledgments
The authors would also like to express their gratitude to CERVECERÍA CUMBRE for providing the brewer's spent grain samples.

The authors appreciate the support of the following Argentine institutions: CONICET (National Scientific and Technical Research Council, Argentina) PUE PROBIEN 22920150100067; The University of San Juan, Argentina (PDTS Res. N° 40/19-CS); ANPCyT (National Agency for Scientific and Technological Promotion, Argentina) - MINCyT (PICT 1390–2017; PICT 2019-01810); IDEA (Res. 0272-SECITI-2019, San Juan Province, Argentina); The University of Comahue, PIN 2017–04/ 1223. Maria Paula Fabani, Juan Pablo Capossio, Rosa Rodriguez, and Germán Mazza are Research Members of CONICET.