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Effect of Drying Methods and Processing Conditions on the Quality of *Curcuma longa* Powder

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Abstract: Turmeric (*Curcuma longa*) is a spice that has been used for a long time in traditional medicine for its anti-inflammatory properties and recently used in the food industry for its dyeing and flavoring properties. This work studied the effect of different drying methods (convection oven drying, fluidized bed drying, and traditional solar drying) on the quality of *Curcuma longa* powder. The effect of UV radiation on turmeric powder using different packaging materials (glass, aluminum foil bag, and low-density polyethylene bag), was also studied. Subsequently, the fluidized bed drying method was used to evaluate the effect of drying temperature. The results show that convection and fluidized bed drying had no significant impact on turmeric quality. However, solar drying degraded curcuminoids by 36.5% and the ORAC value decreased by 14%. Regarding the packaging materials, the aluminum bag prevented the deterioration of 14% of the curcuminoids for the powder exposed to UV radiation. Finally, the effect of temperature on fluidized bed drying was evaluated at 50–80 °C, finding that there were no significant differences in the curcuminoid content and antioxidant capacity of turmeric powder. This implies that the range of temperature used in this study is appropriate for drying this material using fluidized bed drying, producing a turmeric powder with a high content of bioactive compounds, when compared to convection oven and solar drying. Therefore, the turmeric powder obtained in this way can be used as an active ingredient in the formulation of different kinds of foods and supplements.

Keywords: *Curcuma longa*; drying methods; antioxidant capacity; curcuminoids; packaging

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1. Introduction

Turmeric root (*Curcuma longa*) is widely used for culinary, medicinal, and cosmetic purposes and as a dietary supplement. It is a rhizomatous small perennial plant belonging to the *Zingiberaceae* family, native to India. It is distributed throughout tropical and subtropical regions of the world and widely cultivated in Southeast Asia [1–3], where it is used as a natural coloring and as a flavoring agent, especially for curries, as well as for dyeing [4]. India and other Asian countries like Bangladesh, Pakistan, Sri Lanka, Taiwan, China, Myanmar, Indonesia, and Thailand are the lead growers of this crop [5]. However, turmeric is farmed in many warm regions of the world [6]. There are several reports of turmeric's health-promoting properties, such as antioxidant activity and anti-infectious, anti-inflammatory, anti-microbial, anti-viral, anti-carcinogenic, and anti-tumor properties [2,3,5,7,8], making it an appealing ingredient to develop functional foods. Globally, the demand for turmeric has grown due to its therapeutic functions and low toxicity [3]. Turmeric has become a relevant crop in Colombia, given its multiple uses and ease of processing into other products (e.g., powder and oleoresin). Its ease of processing promotes its use in traditional agriculture areas and as an alternative for illegal crops (United Nations Office on Drugs and Crime—UNODC, 2020). As of 2020, 50.2 hectares of turmeric were

cultivated in Colombia and 755 tons were produced, with a yield of 15.44 ton/ha. Each ton was valued at USD 1610 (Ministerio de Agricultura de Colombia, 2020; Ministerio de Agricultura de Colombia, 2021) [9].

The major bioactive compounds in the turmeric rhizome are curcuminoids, phenolic acids, and flavonoids, which possess health-promoting properties [5]. These properties are mainly related to curcuminoids, a group of phenolic compounds comprising of curcumin, dimethoxy curcumin, and bisdemethoxycurcumin [2,10]. Curcuminoids are the main dyes of turmeric; they belong to a group of phenolic compounds called diarylheptanoids. Three main curcuminoids have been identified: curcumin—((1E,6E)-1,7-bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione), desmethoxycurcumin—((1E,6E)-1-(4-Hydroxy-3-methoxyphenyl)-7-(4-hydroxyphenyl)hepta-1,6-diene-3,5-dione), and bisdemethoxycurcumin—((1E,6E)-4-hydroxyph enyl)-7-(4-hydroxyphenyl)hepta-1,6-diene-3,5-dione). There are reports of curcuminoid's antioxidant [11], anti-inflammatory [12], anticancer [13]), and antimicrobial [14] properties. Additionally, they have shown to have a potential effect on neurodegenerative diseases and atherosclerosis [15–17]. Curcuminoids are not stable in the presence of light, especially in solutions. Some studies report that curcumin shows photodegradation when exposed to UV/Visible radiation, in both solution and on solid-state thin film. Several degradation products have been reported, including products from the cyclization of curcumin [18]. Additionally, certain processing conditions or exposure to UV radiation in storage could affect the stability and bioactivity of curcumin [19].

In the market, turmeric is generally found fresh or dried (powder). Currently, turmeric production is about 37,000 tons, valued at USD 40,160,000,000 [5]. Commercially, the powder is the most convenient presentation of turmeric [20] because it can be used directly as a spice and for turmeric oleoresin and oil manufacturing [21]. Therefore, the demand for dried turmeric is increasing in global markets [7]. Turmeric powder comes from the plant rhizomes, involving various post-harvest processes comprising of disinfection, drying, milling, and packing. These post-harvest treatments could affect the quality of turmeric powder [22] since they affect the content and stability of curcuminoids.

Drying or dehydration is the most widely used technique for turmeric preservation [5]. Convection oven drying, freeze drying, vacuum drying, solar drying, and osmotic drying are some drying techniques developed in the past and during recent years [23]. Solar drying is the traditional method used for obtaining turmeric powder. The climate conditions in tropical countries make solar energy practically attractive for food drying processes [24]. In this regard, solar drying is an adequate solution for developing countries that lack convectional energy resources but have a constant solar input throughout the year [25]. However, the choice of optimal processes would determine the physicochemical and functional properties of the final product. Some studies reported that solar drying decreases the overall content of curcuminoids [26]. Others have found that drying does not affect their content [26,27]. However, there are no records on the effect of fluidized bed drying on the curcuminoid content of turmeric powder.

On the other hand, packaging is another postharvest process that can significantly affect the quality of the final product. The packaging material is a critical factor that can protect and delay the formation of different compounds such as ((2Z,5E)-2-hidroxi-6-(4hidroxi-3-metoxifenil)-4-oxohexa-2,5-dienal, ferulic acid, and feruloilmetane, which result from the contact of turmeric with oxygen and light transmission through the packing [28]. The findings of previous studies have demonstrated that undesirable effects of gamma radiation on food products—such as softening, breathing, or lipid oxidation—are significantly diminished by modified atmosphere packaging [29]. Some authors evaluated the effect of gamma irradiation under various packaging atmospheres (air, N_2, and vacuum) on the physicochemical properties of turmeric powder [30]. However, there are no studies evaluating the effect of packaging materials on turmeric powder's properties, which is a crucial factor in food preservation. For instance, Fikreyesus et al. (2021) assessed the influence of packaging material on the physicochemical, microbial, and sensory properties of infant powder meal using paper, polyethylene, and polypropylene bags. They reported

that powder meals are a moisture-sensitive product, and long-term storage using permeable packaging materials can lead to moisture absorption from the powder. On the other hand, Tripetch and Borompichaichartkul (2019) studied the effects of packaging materials (high-density polyethylene (HDPE) bag and jute sack) and storage time on the phenolic content, chlorogenic acid, and antioxidant capacity variations in arabica green coffee beans. The authors found that there were no significant differences in the content of phenolics in coffee beans during four months of storage for both types of packaging, but after one year of storage, the content of phenolics and antioxidant capacity of coffee beans stored in a jute sack were higher than those stored in an HDPE bag [31].

Therefore, the objective of this study was to evaluate the effect of drying methods, drying temperature, and packaging material on the curcuminoids' content, antioxidant capacity, and color, which are parameters directly related to the quality of turmeric powder.

2. Materials and Methods

2.1. Reagents

6-Hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox) was obtained from Biosynth Carbosynth (Berkshire, UK); 2,2′-Azobis(2-methylpropionamidine) dihydrochloride (AAPH) and gallic acid from Sigma-Aldrich (Saint Louis, MO, USA); fluorescein sodium from Chem-Impex International, Inc (Wood Dale, IL, USA); methyl-beta-cyclodextrin from ACROS Organics™ (Fisher Scientific GmbH, Schwerte, Germany); sodium carbonate and Folin-Ciocalteu's Reagent from ITW Reagents (PanReac-AppliChem, Barcelona, Spain); phosphate buffered saline (Dulbecco A) tablets from Oxoid Limited (Hampshire, England); curcumin from Dr. Ehrenstorfer GmbH (Augsburg, Germany); desmethoxycurcumin and bisdemethoxycurcumin from Chengdu Biopurify Phytochemicals Ltd. (Chengdu, China); and analysis-grade acetone, ethanol, methanol, acetic acid, hexane, and LC/MS-grade acetonitrile from Merck KGaA (Darmstadt, Germany). Additionally, dichloran glycerol agar 18% was obtained from Merck KGaA (Darmstadt, Germany).

2.2. Vegetal Material

Fresh turmeric (*Curcuma longa*) rhizomes were collected from local farmers in Uramita, Antioquia, Colombia (06°52′37.2″ N, 76°12′03.1″ O). This research used rhizomes with no mechanical affectations and free of damage caused by pathogens and insects. The rhizomes were washed to remove all physical contaminants. After washing, they were dried with a paper towel to remove any excess moisture and subsequently disinfected. The disinfection was carried out by immersion in a solution of organic acids at 0.5% *v/v* Biodes-Ultra (Cory Industries, Medellín, Colombia), as has been reported for other food matrices [32,33]. This process is necessary to destroy microorganisms that may be present in the rhizomes. Afterwards, they were stored under refrigerated conditions (0–5 °C) until further analysis.

2.3. Drying Experiments

Before drying, the rhizomes were sliced in a food processor (Sammic, Spain) to obtain slices of 5 mm thickness. Samples were processed in batches and were immediately submitted to the respective drying experiment to prevent enzymatic browning [26]. Three drying methods were studied: traditional solar drying (TSD), fluidized bed drying (FBD), and convection oven drying (COD). The drying experiments were conducted until constant weight, with an upper limit of 8% (wb) (ICONTEC, 2021) [34].

2.3.1. Traditional Solar Drying (TSD)

For TSD, sliced rhizomes were spread into a uniform layer (1 cm of thickness) over a perforated aluminum tray (70 cm × 50 cm) and exposed to direct sunlight (from 8 am to 6 pm). The material was carefully homogenized by hand, using gloves (every hour, approximately). TSD conditions comprised of an average temperature of 24 ± 2 °C for product surface, and a relative humidity of 76 ± 0.5%. The drying was carried out until

constant weight was achieved. The pyranometer of SIATA (Sistema de Alerta Temprana del valle de Aburrá) station was utilized to monitor the solar radiation intensity.

2.3.2. Convection Oven Drying (COD)

The COD was performed in a Memmert model UF 260—Schutzart DIN 40050—IP20 oven (Schwabach, Germany). Samples were also spread into a 1 cm thick layer on a perforated aluminum tray (25 × 30 cm). COD was conducted at 50 °C and dried to a constant weight.

2.3.3. Fluidized Bed Drying (FBD)

FBD was performed in a fluidized bed dryer (Vibrasec S.A.S., Medellín, Colombia). FBD conditions consisted of a 2400 rpm fan (equivalent to an air velocity of 1.0 m/s) and a temperature of 50 °C. Samples were dried to a constant weight.

2.4. Turmeric Powder Production

The dried turmeric slices obtained with different drying methods were milled to a powder (40 µm particle size) in a hammer mill (Vibrasec S.A.S., Medellín, Colombia) and then stored in aluminum sealable bags at 25 °C and 75% relative humidity conditions until analysis.

2.5. Turmeric Powder Characterization

2.5.1. Moisture Content and Water Activity

The moisture contents of fresh turmeric and dried turmeric were determined according to AOAC methods, using a gravimetric method, drying at 105 °C in an air oven to constant weight. Water activity was measured at 25 °C using a dewpoint hygrometer (AQUALAB-PRE) (AOAC, 2000). Triplicate analyses of each sample were carried out (n = 3).

2.5.2. Determination of Curcuminoid Content

Curcuminoid content was determined by HPLC-DAD UltiMate™ 3000 with software Chromeleon 7.2. (Dionex, Thermo scientific, Sunnyvale, CA, USA), using a reverse-phase Hypersil GOLD C18 column (100 mm × 2.1 mm ID, the particle size of 1.9 µm; 0.2 µm × 2.1 mm ID prefilter) (Thermo Scientific™, Waltham, MA, USA). The mobile phases were 0.3% acetic acid in water (A) and 0.3% acetic acid in acetonitrile (B). The gradient was isocratic (35% of A and 65% of B), the flow rate was 0.3 mL/min, the injection volume was 10 µL, and the detector was set at 420 nm. The column temperature was maintained at 30 °C.

The individual contents of curcuminoids were determined by UPLC-DAD, using a modified procedure based on Cheng et al. (2010) [35] for fresh rhizomes and turmeric powder. Curcuminoids were quantified from external standard calibration curves of curcumin, desmethoxycurcumin, and bisdemethoxycurcumin methanolic solutions. A total of 0.25 g ± 0.01 g of the turmeric powder were weighed in a centrifuge tube and added to 10 mL of hexane. This mixture was homogenized for 5 min and centrifuged at 4000× *g* rpm for 5 min. The supernatant was discarded, and the remaining hexane was evaporated inside a Resprep Quick-Replace Vacuum Manifold (Restek Corporation, Bellefonte, PA, USA). Then, the solid was reconstituted with 25 mL of ethanol, sonicated at room temperature for 5 min, homogenized for 5 min, and centrifuged at 4000× *g* rpm for 5 min. The resulting supernatant was diluted at 1:200 with the mobile phase. Triplicate analyses of each sample were carried out (n = 3).

2.5.3. Determination of Antioxidant Capacity

Sample preparation was carried out according to the method previously described by Cao et al. [36]. Briefly, 0.20 g ± 0.01 g of turmeric powder was weighed in a centrifuge tube and added with 5 mL of hexane. This mixture was homogenized for 1 min, sonicated at room temperature for 10 min, and centrifuged at 4000× *g* rpm for 15 min. The supernatant

was transferred to a screwed amber vial. The previous lipid extraction was conducted twice, and both supernatants were united in the same vial. The hexane of this extract was completely evaporated inside a Resprep Quick-Replace Vacuum Manifold (Restek Corporation, Bellefonte, PA, USA). Later, the residue was reconstituted with 2 mL of acetone, and this mixture was thoroughly mixed. This extract was reserved under freezing conditions (−20° C) until the ORAC-lipophilic assay. The lipophilic extract was diluted at 1:50 in 10 mM phosphate-buffered saline solution (PBS). Then, 1000 µL of the diluted sample was placed in a screwed vial, and 150 µL of the 7% methyl-beta-cyclodextrin solution (in water: acetone, 50:50) was added. This mixture was homogenized for 10 s.

For the hydrophilic extract, the hexane was evaporated inside a Resprep Quick-Replace Vacuum Manifold (Restek Corporation, Bellefonte, PA, USA). Then, 5 mL of extraction solvent (acetone: water: acetic acid, 70:29.5:0.5) were added to the dried powder. This mixture was homogenized for 1 min, sonicated at room temperature for 6 min, and centrifuged at 4000× *g* rpm for 15 min. The supernatant was reserved under freezing conditions (−20 °C) until the ORAC-hydrophilic assay. The hydrophilic extract was diluted at 1:10 in 10 mM PBS.

The antioxidant capacity of fresh turmeric and turmeric powder was determined by the ORAC method, following Akter et al. [37]. The ORAC-lipophilic and ORAC-hydrophilic assays were performed on a multimode microplate reader Varioskan™ LUX equipped with a SkanIt RE 6.0.1. Software (Thermo Scientific™, Waltham, MA, USA). Trolox standards were prepared in 10 mM PBS (5–600 µM). The reagents were added to each of the wells of an ELISA black plate as follows: 150 µL of 1 µM fluorescein and 25 µL of the sample (either lipophilic, hydrophilic dilutions, blank, or standard). Samples were incubated in the dark at 37 °C for 30 min. Then, 25 µL of 250 mM AAPH was added to each well. Finally, the fluorescence was measured at 485 and 520 nm (in kinetic intervals of 30 s, for 1.5 h, and at a constant temperature of 37 °C). The ORAC-lipophilic and ORAC-hydrophilic results of the turmeric powder were extrapolated from the calibration curve as micromoles of Trolox equivalents per gram of turmeric powder (µmol TE/g). Quantifications were made in triplicate. The total ORAC value was obtained by adding the ORAC-lipophilic and the ORAC-hydrophilic results.

2.5.4. Color Measurements

The color of rhizomes was determined with a Nanocolor UV/VIS Machery–Nagel set to D65 illuminant and a 10° observation angle. The CIELAB color space was used to determine the parameters: L* (black (0) to White (100)), a* (greenness (−) to redness (+)) and b* (blueness (−) to yellowness (+)). The mean values were obtained from triplicate readings. The total color difference (ΔE) was determined according to Equation (1) [30].

$$\Delta E = \sqrt{(\Delta l)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

These solutions were prepared by taking 25 mg of flour and 50 mL of ethanol. The mixture was stirred for 20 min at room temperature (25 ± 2 °C). The mixture was centrifuged at 3000× *g* rpm at 20 °C. This solution was added using a quartz cell for reading [36].

2.6. UV Radiation Effect Using Different Packaging Materials

The three packing materials used were glass, aluminum foil bag, and low-density polyethylene (LDPE) bag. Also, unpackaged turmeric powder was used as a control. For these tests, small quantities (1 g) of powder were employed so that packaged material formed a thin sheet of powder inside the package (2 mm wide). The thin layers of the sample received radiation from a UV lamp. The radiation and power were 360 nm and 6 W, respectively.

The samples were exposed to radiation for 9 h at room temperature (25 ± 2 °C). Tracking of samples was conducted to analyze the content of curcuminoids and antioxidant capacity. Color assessment was also made. The assay was performed in triplicate.

2.7. Effect of Temperature of Drying

One of the three dehydration methods (TCD, FBD, COD) was selected to continue the research based on the curcuminoid content and antioxidant capacity (ORAC assay) results.

For the selected drying method (FBD), the effect of temperature (40, 50, 60, 70, and 80 °C) on the functional properties of turmeric powder (curcuminoid content and antioxidant capacity) was determined as well as the moisture content and water activity.

Finally, drying curves for each temperature were analyzed. Weight changes of turmeric during the drying process were monitored by taking samples at every 1 h interval, with a digital balance (0.001 g). Samples were dried to a constant weight.

A dimensionless moisture ratio (MR) was calculated from the drying curves using the following Equation (2):

$$MR_t = \frac{X_t - X_e}{X_o - X_e} \quad (2)$$

where X_t is the moisture content at any time t (g water/g dry basis), X_e is the moisture content at the equilibrium (g water/g dry basis), and X_o is the initial moisture content (g water/g dry basis). Values of X_e are considered to be relatively small compared to X_t or X_o. Thus, $(X_t - X_e)/(X_o - X_e)$ can be simplified to (X_t/X_o) [37].

2.8. Statistical Analysis

Statistical analysis was performed using GraphPad Prism 5 software (GraphPad Software, Inc., San Diego, CA, USA) and Statgraphics Centurion XVII (Statpoint Technologies, Inc., Warrenton, VA, USA). The response variables were analyzed by an analysis of variance (ANOVA), and the means were compared using the Tukey test at a 95% significance level to determine the significant differences between samples.

3. Results

3.1. Drying Experiments Results

Table 1 shows the moisture content, water activity, and drying time results for each drying method and for fresh turmeric rhizomes. The drying was conducted until a constant weight was reached, obtaining different drying times for each treatment: TSD required 20 h, while COD and FBD needed 13 and 5 h, respectively. As expected, for all the dehydration methods, the moisture content (weight basis, wb) of the samples decreased, and the lowest value was obtained with the FBD process (7.5%). Additionally, the lowest a_w was achieved with FBD, which ensured better stability since the values reported in Table 1 for TSD and COD were located in the region of fungal, yeast, and bacterial growth [36]. TSD was the drying method that required the longest time, since this occurs through incident solar radiation. Several authors have reported a longer drying time for the TSD than for hot air drying [38].

Table 1. Moisture content and water activity for fresh and dried turmeric.

Drying	Moisture Content (% *w*/*w*)	Time (h)	a_w
Fresh Turmeric	83.2 ± 0.5	——	0.81 ± 0.003
TSD	7.9 ± 0.2 [a]	20	0.08 ± 0.003 [a]
COD	7.6 ± 0.1 [a]	13	0.07 ± 0.003 [a]
FBD	7.5 ± 0.2 [a]	8	0.05 ± 0.003 [b]

Data are expressed as mean ± standard deviation (n = 3). Common letter in the same column indicates that they are not significantly different ($p < 0.05$).

3.1.1. Curcuminoid Content

The results show that the three drying methods, TSD, FBD and COD, affected the total curcuminoid content of the rhizomes. The kinetics of degradation of total curcuminoids for the three drying methods is shown in Figure 1.

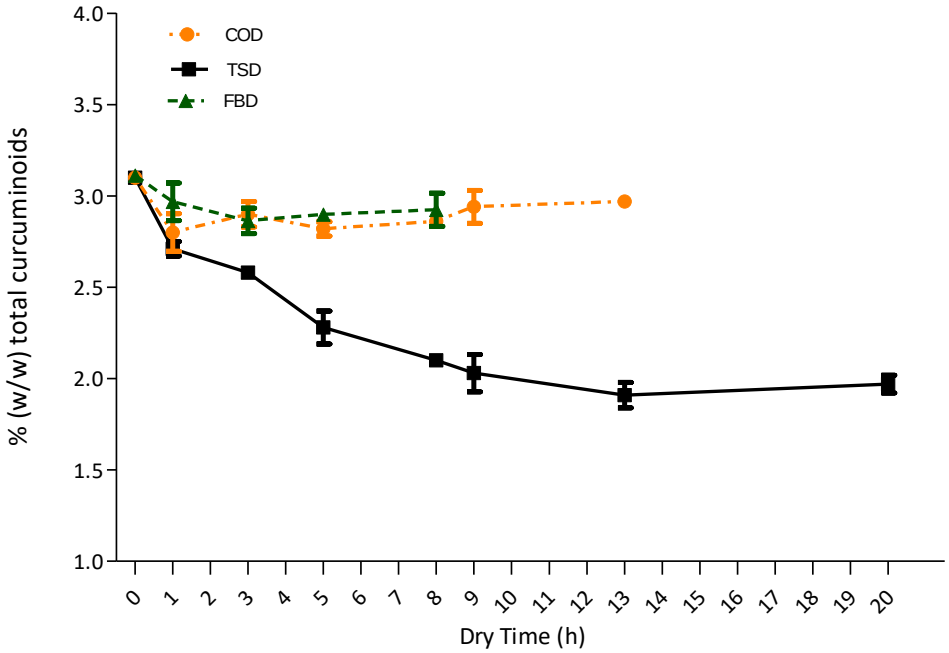

Figure 1. Degradation kinetics plot of total curcuminoids content, for convection oven drying (COD), solar drying (TSD), and fluidized bed drying (FBD).

TSD had a significant effect on the curcuminoid content. TSD decreased the curcuminoid content by 36.5%, in contrast to the fresh sample. This behavior was constant throughout the drying process (see Figure 1), since drying occurs through incident solar radiation (5.408 $kWhm^{-2}$). TSD, due to the low and inconsistent temperatures, takes longer to dry, which generates losses in the quality of the product [39]. On the other hand, COD and FBD presented a slight decrease in the curcuminoid content, resulting in a reduction of approximately 2% and 1.9%, respectively.

Some studies report that curcumin is stable up to temperatures of 190 °C, according to differential scanning calorimetry analysis (DSC) [5]. In our study, all the dryings were performed between 24 and 50 °C, thus, within this temperature range, curcuminoids are non-thermolabile. However, for TSD, the rhizomes were exposed to UV radiation. Previous studies on turmeric oleoresin have reported photodegradation processes of curcuminoids (curcumin, desmethoxycurcumin, and bisdemethoxycurcumin) [40]. Other authors have found that curcumin undergoes photodegradation in solution and solid form [41]. The latter could explain the progressive reduction in total curcuminoid content from the TSD samples.

Prathapan et al. (2009) measured the total curcuminoid content of turmeric at the end of the solar drying process. They observed a reduction in the concentration of curcuminoids [26]; however, they did not measure the curcuminoid content throughout the drying process as we did in the present study. We obtained a higher curcumin reduction rate (36.5%) for TSD than that reported in the Prathapan et al. study (18%) [26]. These discrepancies could be related to turmeric crop origin, the edaphoclimatic conditions of the soil, and the postharvest treatments before drying. Given that TSD decreases the concentration of curcumin, desmethoxycurcumin, and bisdemethoxycurcumin [7], the decline of these metabolites impacts the physicochemical and functional properties of turmeric powder (*Curcuma longa*) quality.

As can be seen in Figure 1, the other drying methods (COD and FBD) preserved the quality of the turmeric rhizomes, i.e., curcuminoids content and antioxidant capacity. For instance, FBD did not affect the content of curcuminoids and the antioxidant capacity of turmeric at the end of the process and presented a shorter drying time when compared to COD. FBD is a technique used in the food industry for various types of products; it has some advantages over TSD and COD: shorter drying periods, color retention, and

preservation of bioactive compounds [19]. Other benefits include greater thermal efficiency, low costs, and easy control [42]. Therefore, the quality of the turmeric powder is best preserved with this drying method.

3.1.2. Antioxidant Capacity

The results for antioxidant capacity (ORAC) are shown in Figure 2. TSD had a significant effect on the antioxidant capacity of the rhizomes since the antioxidant capacity had reduced by 15% at the end of the drying (20 h). COD did not present a significant decrease in the ORAC value (1.8%). The reduction for FBD was only 0.2%.

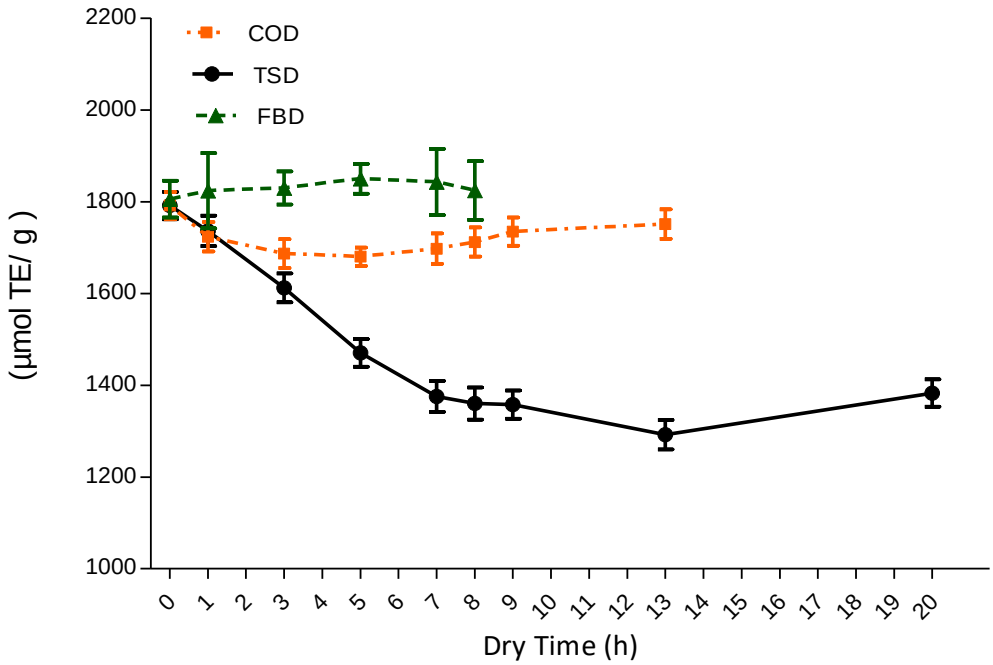

Figure 2. Effect drying treatments in curcuma longa rhizomes. Variation of antioxidant capacity (ORAC) of rhizomes during TSD, COD, and FBD.

There is strong evidence correlating antioxidant capacity with a higher content of curcuminoids since these bioactive compounds present antioxidant properties [12,43]. However, Sing et al. (2010) reported other active substances with antioxidant capacity in turmeric, such as ar-turmerone and alpha-turmerone, the main constituents of essential oil and oleoresin [44]. The authors suggest that these compounds probably exert synergistic or additive effects to the total antioxidant capacity because this reduction in antioxidant capacity is not equivalent to the same content reduction present in curcuminoids. In addition, according to Chumroenphat et al. (2021), curcumin is degraded and transformed into other phenolic compounds, particularly vanillin and ferulic acid, during the drying processes [41]. This degradation could be responsible for the final increase in the antioxidant capacity of TSD.

The photodegradation analysis showed a decrease in scavenging activities against DPPH radical [45], which may be associated with curcuminoid degradation. The decline in the concentration of curcumin, desmethoxycurcumin, and bisdemethoxycurcumin directly affects the antioxidant capacity since these substances have antioxidant properties following the hydrogen atom transfer (HAT) and single electron transfer (SET) mechanisms [46] and are the main bioactive compounds of turmeric.

FBD presented the best performance in drying time, moisture content, water activity, and preservation of the antioxidant capacity and total curcuminoid content of the turmeric. Hence, it was selected as the method to continue on in the study, evaluating some processing

conditions. The study variable selected was temperature, i.e., the effect of fluidized bed drying temperature on the curcuminoid content and antioxidant capacity.

3.1.3. Color

Color is often related to the quality of turmeric. Table 2 shows the results for color parameters (L*, a*, and b*) of the turmeric dyed solutions. TSD showed significant differences in b* (yellow/blue coordinate) and L*(lightness). The color difference (ΔE) was used to quantify the potential color change in turmeric samples processed by different drying techniques concerning fresh turmeric. Significant differences in ΔE were observed for all of the drying methods. However, TDS had the greatest effect on total color change, which signifies the highest color difference between the fresh and dried samples. The latter could be due to a decrease in curcuminoid content, which is affected by photodegradation [7]. Moreover, oxidation, thermal degradation, and glycosylation could also explain the previous results [39]. Ray et al. (2022) evaluated the effect of different drying methods (e.g., solar and convective drying) and found the highest color change in convective drying at 60 °C, explaining that intense browning reactions (Maillard), oxidation, and change in the surface structure are the principal causes of degradation of the color [47].

Table 2. Effect of drying treatments on the CIElab parameters.

Drying	Color Analysis			
	L	a	B	ΔE
TSD	90.4± 0.4 [a]	−10.7 ± 0.2 [a]	123.9 ± 0.1 [a]	6,30 ± 0.03 [a]
COD	91.6 ± 0.1 [b]	−11.0± 0.1 [a]	124.9 ± 0.3 [b]	5,1 ± 0.1 [b]
FBD	92.2 ± 0.3 [b]	−10.9 ± 0.2 [a]	125.9 ± 0.3 [c]	4,24 ± 0.02 [c]

Data are expressed as mean ± standard deviation (n = 3). Common letters in the same column indicates that they are not significantly different ($p < 0.05$).

The parameter b* was statistically different for the three treatments, with its highest value in FBD. This solution had a more yellow hue. On the other hand, TSD had the lowest b* value. The latter is because curcuminoids give the characteristic yellow tone to the rhizomes [2], and the TSD sample also showed lower curcuminoid content. The drying method had no effects on the parameter a* (red/green coordinate). Komonsing et al. (2022) showed that the light exposure caused color fading in turmeric slices [7]. In TSD, the sun (light radiation) affects turmeric rhizomes' color, affecting the quality of the powder. Since higher lightness (L*) values are preferable in the case of dried food products [48], the FBD process lead to the best quality in color.

3.2. Effect of Drying Temperature on Curcuminoids Content, Antioxidant Capacity and Drying Time

Following the aforementioned results, fluidized bed drying shortened the drying process of turmeric rhizomes, as compared to convective oven drying and solar drying. Moreover, FBD led to the slightest variation in total curcuminoids content and antioxidant activity with better color preservation and the lowest water activity. Hence, FBD was selected to continue on in the study to evaluate the effect of drying temperature.

The effect of temperature on FBD in the drying curves of turmeric rhizomes is shown in Figure 3. For all temperatures, we observed that the MR value decreased rapidly after the first hour of drying, as observed in Figure 3, being more evident for the temperature of 80 °C. Sharma et al. evidenced a similar trend for hot air drying and direct solar drying methods [41]. In our study, the drying time to reach a final moisture content of less than 8% was 8, 8, 6, and 5 h for 50, 60, 70, and 80 °C, respectively. According to these results, with a temperature of 80 °C, the drying time was reduced by 37.5% as compared to drying at 50 °C. Several researchers have previously reported on the dependence of drying time on temperature. This behavior is due to higher temperature increasing the system's enthalpy, which increases the transfer of mass and energy, accelerating the migration of water [49].

Chan and Kuo (2018) evaluated different temperatures (80, 100, 120 °C) in a fluidized bed dryer on wheat germ, finding that the efficiency of dehydration was better at a higher set temperature (120 °C). Additionally, shorter drying times might be recommended for a hot and humid environment such as the summer season in Asia [50].

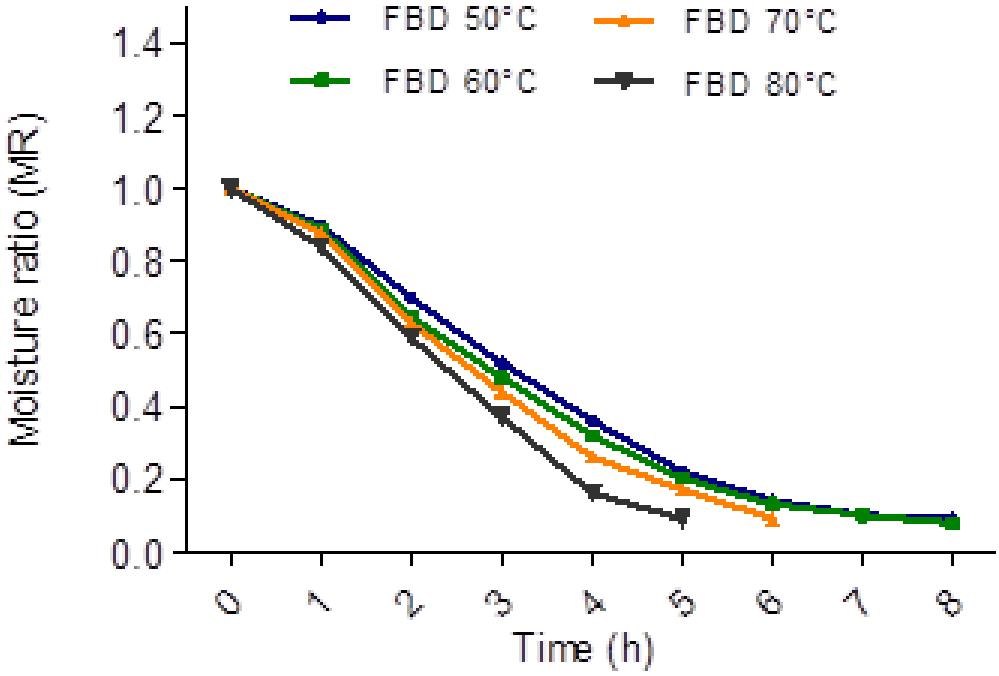

Figure 3. Fluidized bed drying kinetics at different temperatures.

Regarding the effect of temperature on curcuminoid content and antioxidant capacity, the results are shown in Table 3. Statistical analysis shows there were no significant differences ($p > 0.05$) in the curcumin, desmethoxycurcumin, and bisdemethoxycurcumin concentration between the dried products obtained under different drying conditions (50 °C, 60 °C, 70 °C and 80 °C).

Table 3. Effects of drying temperature of FBD on curcuminoid content and antioxidant capacity in turmeric powder and fresh turmeric.

Temperature (°C)	Curcumin (% *w/w*)	Demethoxy-Curcumin (% *w/w*)	Bisdemethoxy-Curcumin (% *w/w*)	Total Curcuminoids (% *w/w*)	ORAC (μmol TE/g)	a_w	Moisture Content (% *w/w*)
Fresh	2.55 ± 0.35 [a]	1.09 ± 0.14 [a]	0.66 ± 0.09 [a]	3.53 ± 0.73 [a]	1805.45 ± 39.99 [a]	0.85± 0.01 [a]	83.2 ± 0.5 [a]
50	2.73 ± 0.38 [a]	1.36 ± 0.18 [a]	0.87 ± 0.11 [a]	3.15 ± 0.64 [a]	1854.35 ± 81.88 [a]	0.051 ± 0.005 [b]	7.5 ± 0.2 [b]
60	2.39 ± 0.33 [a]	1.01 ± 0.16 [a]	0.83 ±0.11 [a]	3.43 ± 0.72 [a]	1851.48 ± 71.98 [a]	0.050 ± 0.004 [b]	7.4 ± 0.2 [b]
70	2.70 ± 0.38 [a]	0.92 ± 0.15 [a]	0.76 ± 0.099 [a]	3.33 ± 0.71 [a]	1826.19 ± 63.91 [a]	0.042 ± 0.005 [b]	7.4 ± 0.3 [b]
80	2.56 ± 0.35 [a]	1.15 ± 0.21 [a]	0.85 ± 0.119 [a]	4.054 ± 0.78 [a]	1733.04 ± 35.94 [a]	0.041 ± 0.005 [b]	6.7 ± 0.2 [b]

Data are expressed as mean ± standard deviation (n = 3). Common letter in the same column indicates that they are not significantly different ($p < 0.05$).

Previous studies evaluated the degradation of curcuminoids at different temperatures with light exposure, showing that light radiation can accelerate the drying process but detriments the curcuminoid content [7]. Although curcumin is stable above 100 °C in thermogravimetric (TGA) studies [41], these correspond to isolated curcumin. On the contrary, there are no reports of the stability of curcuminoids (curcumin, desmethoxycurcumin, and bisdemethoxycurcumin) in turmeric powder obtained from FBD. In our study, FBD-dried rhizomes did not receive light radiation. Thus, we could observe that the functional properties of the turmeric powder prevailed at all the evaluated temperatures.

The results from HPLC-DAD show that curcumin was the most abundant curcuminoid in the turmeric powder, followed by bisdemethoxycurcumin and desmethoxycurcumin,

which is consistent with a previous report [51]. Additionally, the concentration of the curcuminoids was stable at the different drying temperatures without showing significant degradation. Prathapan et al. (2009) found no significant differences in curcuminoid content when compared with fresh and thermally treated material (70, 80, 90, and 100 °C for 30 min) [26]. However, they also observed that solar drying significantly decreased the concentration of the curcuminoids [26].

On the other hand, from Table 3, it can be seen that there were no significant differences in antioxidant capacity, as assessed by ORAC method, in samples dried at 50, 60, 70, and 80 °C and fresh turmeric, thus preserving the functional properties of turmeric. Another study evaluated the effect of different drying temperatures (40, 50, 60, 70, and 80 °C) on the antioxidant capacity through DPPH, ABTS, FRAP, and TPC methods [7]. They also reported no significant changes in antioxidant capacity with temperature variation. The various types of antioxidants in turmeric also contribute to the overall antioxidant capacities and could explain the previous statement. Phenolic compounds of turmeric include gallic acid, curcumin, ferulic acid, epicatechin, catechin, cinnamic acid, protocatechuic acid, chlorogenic acid, rutin, genistein, and coumarin [7]. Therefore, although the antioxidant capacity of the flour is mainly related to the content of curcuminoids [12,46], these other substances also contribute to the total antioxidant capacity of turmeric flour.

For moisture content and Aw, we determined that higher drying temperatures led to lower moisture content and water activity of the turmeric powder (see Table 3). This has also been reported for other food matrices [38,52,53]. Additionally, this decrease helps reduce the risk of microbiological contamination [54], making the product more stable.

According to the information presented above, FBD at temperatures from 50 °C to 80 °C did not affect the quality of the turmeric powder but affected the drying time, obtaining a shorter drying time at 80 °C. This reduction in time can be significant since, in small processing plants that have drying equipment of this type (which is the case of several drying plants in Colombia), it allows for the continuation of the grinding and packing process in less time, without altering the final quality of the product.

3.3. UV Radiation Effect Using Different Packaging Materials

We studied the effect of UV radiation on the quality of turmeric powder, packaged in different materials: glass, low-density polyethylene, and an aluminum foil bag (see Figure 4). The content of curcuminoids decreased by 14% for the unpackaged powder (control) after 1.3 h of exposure. For glass-packaged powder, the concentration of the curcuminoids declined by 9.6%, while for LDPE and aluminum foil, the decline was 8% and 3.2%, respectively.

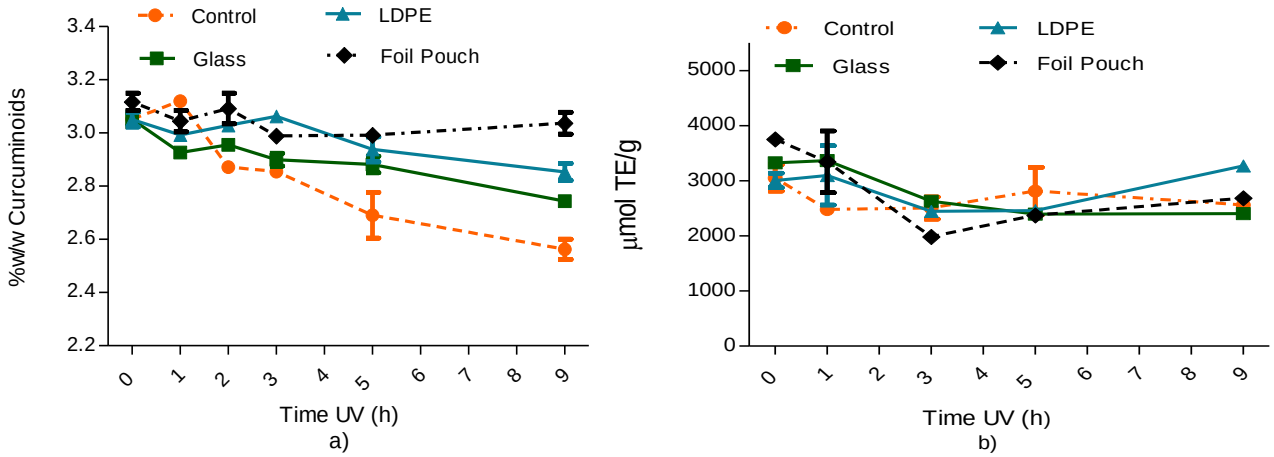

Figure 4. Effect of UV radiation on curcuminoid content using different packaging materials for turmeric powder. (**a**) Variation of curcuminoid content vs. time. (**b**) variation of the antioxidant capacity of the powder vs. time.

The antioxidant capacity of turmeric flour after exposure to UV radiation did not change significantly with time or with the packaging material. The color analysis of the UV-radiated turmeric powder showed an effect on the coordinate a*. Unpackaged powder presented a greener hue, while packaged samples showed no significant difference in color parameters, as shown in Table 4. The comparison of the total color change between the packaging materials did not show a significant difference between them.

Table 4. UV radiation effect on the CIElab parameters of turmeric powder.

Packing Material	Color Analysis			
	L	A	B	ΔE
Control	96.3 ± 1.6^{a}	-5.0 ± 0.1^{a}	119.9 ± 0.3^{a}	7.86 ± 0.06^{a}
Glass	93.5 ± 0.9^{b}	-3.9 ± 0.2^{b}	119.4 ± 1.2^{a}	8.9 ± 0.9^{a}
LDPE	$94.0 \pm 0.7^{a,b}$	-3.8 ± 0.1^{b}	120.0 ± 0.8^{a}	8.4 ± 0.6^{a}
Foil Pouch	$93.8 \pm 0.7^{a,b}$	-3.9 ± 0.1^{b}	118.9 ± 0.4^{a}	9.3 ± 0.3^{a}

Data are expressed as mean ± standard deviation (n = 3). Common letters in the same column indicates that they are not significantly different ($p < 0.05$).

All the packaged powders were similar in terms of a*. Direct exposure to UV radiation can lead to photodegradation reactions that favor oxidation processes that generate compounds increasing the green hue.

Photoreactions affect the nutritional composition (i.e., fats, vitamins), the color, and the concentration of bioactive compounds in several foods, such as curcuminoids in turmeric. Therefore, these products might have a shorter shelf life [55]. Metalized bags, such as aluminum foil, have a high barrier against light [55]. In the present study, the aluminum foil protected the turmeric powder and prevented the degradation of curcuminoids and the decline of the antioxidant capacity.

4. Conclusions

The findings of this study show the impact of different drying methods (convection oven drying, fluidized bed drying, and traditional solar drying) on the quality of turmeric powder, as well as the impact of material packaging. The results show that the drying method affected the total curcuminoids content, the antioxidant capacity, and the color of the turmeric. Traditional solar drying reduced the quality of the dried product by 36.5% for curcuminoid content and 15% for ORAC antioxidant capacity while fluidized bed drying led to a reduction of 1.9% and 0.2% on curcuminoids and antioxidant capacity, respectively. Therefore, by choosing a suitable drying method, the quality of the turmeric powder could be preserved. From the three evaluated methods, FBD was the most convenient since it preserved the curcuminoid content, antioxidant capacity, and color of the turmeric with the lowest water activity. Additionally, its drying time was the shortest.

For FBD, temperature variations from 50 to 80 °C did not affect the content of curcuminoids and the antioxidant capacity. Therefore, drying can be performed at 80 °C, which results in the lowest drying time with a similar powder quality.

Finally, the effective protection over curcuminoids content was presented by a foil pouch, followed by LDPE and glass packaging. Thus, the aluminum bag for turmeric powder as a packaging material is suggested as the best option to protect the curcuminoids from photodegradation during storage.

These results are valuable for the food industry, turmeric growers, and the spices/supplements manufacturers to produce a high-quality product that can be commercialized and used as an active ingredient in many formulations.

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