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Optimization of Drying Kinetics and Stone Milling of Chickpea (*Cicer arietinum*): An Investigation of Moisture Content and Milling Speed Effects on Mill Operative Parameters, Particle Size Distribution, and Flour Composition

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Abstract: Chickpeas are one of the most widely consumed legumes in the world. Nevertheless, the literature is lacking studies on the effect of drying and milling processes on chickpea flour characteristics, thus motivating this work. The first aim of this work is to improve chickpea drying process through an in-depth evaluation of drying kinetics; the second aim is to assess the effects of three different moisture contents (8, 10, and 12%) and three milling speeds (120, 220, and 320 RPM) on operative milling parameters, particle size distribution, and flour composition. Our results highlight that moisture content and stone rotational speed have statistically significant effects on milling operative parameters, flour particle size, and chickpea flour composition. As stone rotational speed increases, flour temperature (ΔT), average power, and damaged starch content significantly increases. On the other hand, as moisture content increases, energy consumption and specific milling energy increases, while starch and protein content significantly decrease. The results of this study recommend, for the first time in the literature, optimal values of moisture content and milling speed of chickpea. In conclusion, milling chickpeas with 10% moisture content at 320 RPM (milling speed) seems to be the best compromise between milling operative parameters, particle size, and chickpea flour composition.

Keywords: chickpea flour; chickpea grinding; conditioning; milling optimization; flour particle size distribution

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1. Introduction

Chickpeas are one of the most widely consumed legumes in the world. According to FAO report, the global chickpea production in 2021 was 14.7 million metric tons (85.5% produced by Asian countries) [1]. Given their low cost and the high traditional consumption in South Asia, the Middle East, and the Mediterranean region, chickpeas are considered as an essential food in several countries. Moreover, given their very interesting protein, starch, and fiber content, chickpeas are widely investigated in the literature. Compared to cereals, pulses contain 2–3 times more dietary fiber per 100 kcal of product; therefore, there is a growing interest in the use of chickpea flour in the food industry [2]. The results reported by Rehn et al. (2023) [2] found that inclusion of chickpeas in diets improved total and low-density lipoprotein cholesterol concentrations, insulin sensitivity, and lipid peroxidation. Furthermore, chickpeas are considered as one of the most interesting alternative protein sources due to their low cost and their lower environmental impact [3]. As a result, chickpea cultivation can improve soil fertility by converting atmospheric nitrogen into nitrogenous compounds for plant growth with the aid of symbiotic bacteria like Rhizobium and Bradyrhizobium [4].

Chickpeas are characterized by a seed coat in the outermost part and by starch granules held within the protein matrix in the inner part [5]. With respect to chickpeas composition, the main macronutrients in chickpea are protein (from 21 up to 25%), carbohydrate (40–50%), and lipid (4–6%), while the main micronutrients are calcium, phosphorus, magnesium, iron, and potassium [6]. Chickpeas have been processed using different methods like soaking or conditioning, dehulling, milling, germination, fermentation, irradiation, roasting, and frying to improve functional, sensorial, and nutritional quality [7]. Chickpea flour as an ingredient, or as an improver, has been used in the food industry for a long time since chickpea flour provides several functional properties such as thickening, gelling, and water-holding capacity [6,8,9]. This is primarily due to carbohydrates and proteins [6]. Chickpea flour is usually substituted and/or incorporated into food formulation to improve sensory and nutritional profile of foods [6–10]. Cappelli et al. (2020) [8] found that chickpea flour can be used as an improver in bread production. The substitution with 5% chickpea flour increased dough stability (S), dough strength (W), dough extensibility (L), and bread volume compared to the control (made with 100% ancient wheat flour). These technological properties are mainly due to specific characteristics of carbohydrates (starch) and proteins and to their contribution to the system as objects of replacement or substitution, usually doughs [6,10]. However, in addition to breadmaking, chickpea flour has several applications in the food industry such as bakery products (cookies, biscuits, and cakes), pasta, noodles, meat analogues, and pureed soup [11].

Nevertheless, milling techniques and the associated parameters, such as milling speed, moisture content, particle size distribution, protein quality, and starch damage, significantly affect flour's physicochemical and technological properties [4]. In particular, the selected milling technique, the milling speed, and the moisture content can directly affect flour water-holding capacity, dough rheological properties, and consumer acceptability attributes such as texture, crunchiness, and crispiness [4,12]. Thakur et al. (2019) [13] found remarkable differences in the nutritional content of flours due to distinctive effects of milling forces (shear, compression, attrition, cutting, or impact) in the different milling systems. However, stone mill represents one of the most utilized methods in the food industry for milling of pulses.

As highlighted in an earlier work [12], moisture content and milling speed are essential operative parameters in the production of flour for the food industry. The correct management of these two parameters can affect the quality of flour and the finished products. Nevertheless, the literature is lacking studies that focus on the effect of drying and milling processes on chickpea flour characteristics, thus motivating this work. The first aim of this work is to improve chickpea drying process through an in-depth evaluation of drying kinetics; the second aim of this paper is to assess the effects of three different moisture contents (i.e., 8, 10, and 12%) and three different milling speeds (i.e., 120, 220, and 320 RPM) on the operative milling parameters, the flour particle size distribution, and the chickpea flour composition. These two objectives are for achieving the goal of optimizing agribusiness and agro-industrial equipment for chickpeas drying and milling in terms of design, construction, and operational aspects. Furthermore, considering the absence in the literature of recommendations regarding optimal moisture content and milling speed in chickpea flour production, this paper has the additional aim to suggest optimal values of these key parameters to optimize the milling process, considering a potential improvement in operative parameters and nutritional content of flours.

2. Materials and Methods

2.1. Raw Materials and Drying Kinetics Measurements

Chickpea (*Sultano* cultivar) was kindly provided by Toscana Legumi Bio Ltd. (Florence, Tuscany, Italy). This cultivar is a native variety of the Middle East (Syria) and represents the most widely cultivated variety of chickpea in Italy. Moreover, *Sultano* variety is particularly suitable for chickpea flour production, given its small–medium size and excellent milling aptitude. Chickpeas were purified and carefully selected before further processing. Successively, chickpeas were dried using a laboratory stove (Heraeus UT 6, Thermo Fisher Scientific Ltd, Waltham, MA, USA) to determine moisture content using gravimetry at 105 °C until a constant weight was reached. Drying kinetics measurement of chickpea was performed using a laboratory stove (Heraeus UT 6, Thermo Fisher Scientific Ltd., Waltham, MA, USA) at 55 °C for 72 h. The temperature of 55 °C has been carefully selected since it allows to minimize energy consumption and to optimize chickpea drying process, consistently with other authors [14]. In particular, the drying kinetics of 12 samples was evaluated by removing from the stove one sample every hour for a total of 12 h. This procedure was performed in three replicates.

2.2. Experimental Design

This work assesses differences in chickpea flour yield, flour particle size distribution, milling time, energy consumption, temperature increase, average power, specific milling energy, and chickpea flour composition, as a function of two factors: chickpea moisture content and stone rotational speed. With respect to chickpea conditioning, three moisture contents were tested: 8, 10, and 12%. Regarding stone rotational speed, three levels were tested: 120, 220, and 320 RPM. A full factorial experimental design with three replicates was carried out.

2.3. Description of Chickpea Drying, Conditioning, and Milling Processes

Fresh chickpeas, harvested at 10.5% moisture content, were purified and carefully selected before further processing, to obtain a sample of 18 kg to be assigned to the drying unit operation. Drying was performed using a laboratory stove (Heraeus UT 6, Thermo Fisher Scientific Ltd., Waltham, MA, USA) at the same temperature used during the evaluation of dehydration kinetics (i.e., 55 °C) for 24 h. Successively, the dried chickpeas were divided into 9 samples of 2 kg each, to perform the conditioning unit operation. Conditioning was performed in tightly sealed plastic bowls through the addition of the correct amount of water via a spray atomizer. Moisture content was set at 8, 10, and 12%. Conditioned samples were mixed and left to stand for 24 h before milling, to allow the complete penetration of water into the core [12].

Finally, a sample of 10 g was collected to verify that the moisture content was correct before milling, using gravimetry at 105 °C until a constant weight was reached. The 9 samples of 2 kg, three for each moisture content, were milled at three different stone rotational speeds, 120, 220, and 320 RPM, corresponding to 12.57, 23.04, and 33.51 rad/s, respectively. The whole procedure was performed in three replicates. Milling was performed using a stone mill (M400, I.B. Manufatti Ltd., Appignano, Macerata, Italy). The diameter of the stones was 0.4 m. Finally, the rotational speeds were verified before milling using a contact tachometer (DT-2236, Lutron Electronic Enterprise Ltd., Taipei City, Taiwan).

2.4. Measurement of Milling Operative Parameters

Before milling, the initial temperature of each sample was measured using a food thermometer (LabQuest 2—Vernier Ltd., Hemel Hempstead, UK) equipped with a temperature probe (Go!Temp—Vernier Ltd.). The sequence of samples to be milled in the three replicates was randomized using R statistical software (version 4.3.0) to exclude possible faults due to the sample order. During milling, several operative parameters were measured or calculated using a high-performance power analyzer (FLUKE-190-062-III-S—FLUKE Ltd., Quezon City, Philippines). The instrument was used to determine and record different parameters like milling time (min) and energy consumption (kWh); moreover, average power (kW) and specific milling energy (kJ/kg) were calculated according to the data recorded by the instrument. Immediately after milling, the temperature increase in chickpea flour caused by the milling process was measured with the same food thermometer; furthermore, total yield was determined as the ratio of the weight of the obtained chickpea flour and the initial weight of conditioned chickpea. Finally, 50 g of chickpea flour for each sample was collected and sent to Analytical Food Laboratory (Florence, Italy) for flour characterization and analysis (Section 2.6).

2.5. Evaluation of Flour Particle Size

Particle size distribution of chickpea flour was determined using four circular sieves with different mesh sizes. In particular, the tested mesh sizes were 600, 400, 250, and 125 µm. This allowed to investigate the flour particle size distribution among five different intervals: less than 125 µm, between 125 and 250 µm, between 250 and 400 µm, between 400 and 600 µm, and more than 600 µm. The sifting procedure was performed as follows: 100 g of chickpea flour was placed on a mesh with a 600 µm sieve, stacked on top of the other sieves (from the largest (i.e., 400 µm) to the finest (i.e., 125 µm)). Successively the whole sieving system was fixed on a vibratory sieve shaker machine (IRIS FTS-0200—Filtra Vibración Ltd., Barcelona, Spain) that performed the sieving process for 10 min at a shaking amplitude of 2 mm. Finally, the chickpea flour that recovered in the five intervals was weighted and expressed as yield in percentage.

2.6. Flour Characterization and Analysis

Starch (AOAC 979.10 [15]), damaged starch (AACC 76-31 [16]), protein (AOAC 920.87 [15]), and total polyphenols (AOAC SMPR 2015.009 [15]) were determined by the Analytical Food Laboratory (Florence, Italy) following approved, official methods.

2.7. Statistical Analysis

The effects of moisture content and stone rotational speed were assessed using a fixed effects model, as described by Montgomery (2017) [17]. Specifically, flour yield and particle size distribution, milling time, energy consumption, temperature increase, average power, specific milling energy, and chickpea flour composition were tested with a two-way ANOVA to determine the effects of chickpea moisture content, stone rotational speed, and their interaction. Significance was set at $p < 0.05$. When significance was reached, a post hoc Tukey HSD test was performed. In addition, a correlation analysis was performed using the Pearson Correlation Coefficient (significance of correlation coefficients was tested using Bonferroni test). The statistical analysis was conducted using R software (version 4.3.0).

3. Results and Discussion

3.1. Chickpea Dehydration Kinetics

Figure 1 summarizes the results regarding the dehydration kinetics of chickpeas.

The water removal rate in food products is governed by phenomena of matter, i.e., water and heat convection at the air–product interface, resulting in heating and dehydration of the product surface with consequent water diffusion and heat conduction [18,19]. Three distinct phases can be identified in the unit operation of food dehydration: (1) heating phase; (2) steady-state dehydration phase; and (3) slow-moving dehydration phase [18,19].

As shown in Figure 1, in the first interval, from 0 to 7 h, only 2.78% of water was removed. This clearly highlighted a long heating phase of chickpea mainly due to the reduced initial moisture content of chickpea (i.e., 10.5%) and the high thickness of the seed coat that limits and delays heat penetration, moisture diffusion, and water evaporation [11,18,19]. In the second interval, from 7 to 10 h, higher water loss was recorded (i.e., 5.08%). In this second interval, which corresponds to the steady-state dehydration phase, the heat supplied contributes only to the evaporation of water from the surface, creating a water concentration gradient between the surface and the interior of the product that causes progressive dehydration via diffusion from the core to the exterior [18,19].

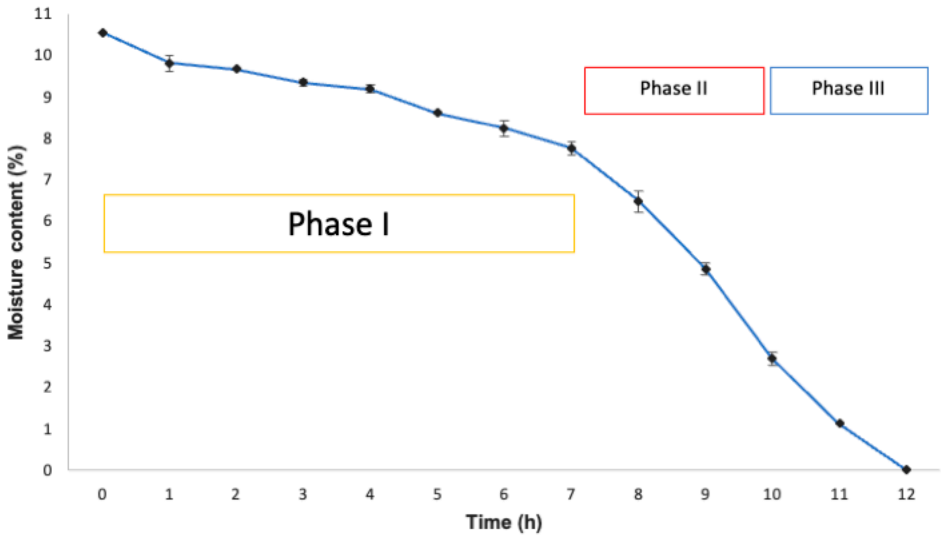

Figure 1. Chickpeas dehydration kinetics expressed as the loss of water content in percentage during drying (12 h). Data points (one sample every hour) represent the mean of the three replicates ± SD. The result of zero percent after 12 h refers to the free water removed from the chickpea samples (approximately 3.00% of bonded water remained in the product).

In the last interval, from 10 to 12 h, the water content decreases via surface evaporation, and the amount of heat used to evaporate it also decreases resulting in an excess of heat at the surface of the product. Despite the result of zero percent reported in Figure 1, approximately 3.00% of bonded water remained in the product. This third interval pointed out the third phase in food dehydration, i.e., the slow-moving dehydration phase [18,19]. Moreover, this results in a lower evaporation rate as well as in a reduction in the water removed from the product [18,19]. As a confirmation of the obtained results, Figure 1 shows a change in the slope of the curve with time. Furthermore, a moisture loss of only 2.69% was recorded. Finally, to the best of authors' knowledge, this is the first work in the literature that clearly describes the chickpea dehydration kinetics, taking a step forward in the comprehension of the dehydration dynamics and the improvement in the unit operation of drying.

3.2. Milling Operative Parameters

The results of milling operative parameters are reported in Table 1.

Table 1. Results of milling expressed as the mean of three replicates ± SD. Letters represents statistically significant differences reported using the Tukey HSD post hoc test for stone rotational speed (a, b, c, d, e, f) and for chickpea moisture content (v, w, x, y, z). Columns without letters are not significantly different.

Sample	Flour Yield (%)	Temperature Increase (°C) (ΔT)	Milling Time (min)	Energy Consumption (kWh)	Average Power (kW)	Specific Milling Energy (kJ/kg)
U 8%, speed 120 RPM	97.66 ± 1.15	8.97 ± 0.61 [a]	47.92 ± 1.42 [av]	0.222 ± 0.01 [v]	0.277 ± 0.01 [a]	418.36 ± 16.40 [v]
U 8%, speed 220 RPM	97.95 ± 0.91	9.13 ± 3.75 [b]	39.19 ± 7.09 [bw]	0.237 ± 0.04 [w]	0.364 ± 0.01 [c]	446.90 ± 75.97 [v]
U 8%, speed 320 RPM	97.17 ± 1.28	14.20 ± 0.92 [c]	31.29 ± 7.85 [bw]	0.240 ± 0.04 [w]	0.466 ± 0.04 [d]	455.34 ± 88.78 [v]
U 10%, speed 120 RPM	97.20 ± 1.31	8.13 ± 2.15 [a]	63.38 ± 10.41 [cx]	0.280 ± 0.04 [x]	0.265 ± 0.00 [b]	518.22 ± 82.44 [w]
U 10%, speed 220 RPM	97.05 ± 0.23	11.50 ± 2.29 [ab]	48.74 ± 16.32 [cx]	0.287 ± 0.09 [x]	0.354 ± 0.01 [c]	532.15 ± 168.20 [w]
U 10%, speed 320 RPM	98.00 ± 0.68	12.13 ± 1.80 [bc]	37.20 ± 10.26 [abvw]	0.284 ± 0.06 [x]	0.461 ± 0.02 [d]	521.57 ± 122.90 [w]
U 12%, speed 120 RPM	97.00 ± 0.67	9.83 ± 0.29 [ab]	93.13 ± 4.01 [dy]	0.448 ± 0.06 [y]	0.288 ± 0.09 [a]	812.92 ± 109.81 [x]
U 12%, speed 220 RPM	97.26 ± 1.41	10.90 ± 1.21 [b]	58.98 ± 5.25 [bcwx]	0.392 ± 0.13 [z]	0.393 ± 0.09 [e]	710.86 ± 239.50 [x]
U 12%, speed 320 RPM	97.91 ± 0.31	12.37 ± 1.15 [c]	45.05 ± 12.60 [bcwx]	0.397 ± 0.13 [z]	0.524 ± 0.03 [f]	712.70 ± 225.16 [x]

With respect to flour yield, the two-way ANOVA did not find any statistically significant differences. Regarding temperature increase (ΔT), the results of the ANOVA found a significant individual effect of stone rotational speed ($p = 0.001$), while this was not the case for moisture content or their interaction. As a result, chickpea flour temperature increases as stone rotation speed increases. Concerning milling time, the two-way ANOVA highlighted individual main effect for stone rotational speed ($p < 0.001$) and moisture content ($p < 0.001$) but not the interaction. On the one hand, stone rotational speed decreased milling time, while, on the other hand, chickpea moisture content increased it [12,20]. As highlighted in an earlier work [12], these results are due to the fact that dry raw materials are more brittle and less resistant than humid and conditioned ones, which show higher plasticity and are more difficult to be milled.

Similar results were obtained for the other operative milling parameters. With respect to energy consumption, the results of the ANOVA found a significant individual effect of chickpea moisture content ($p < 0.001$), while this was not the case for stone rotational speed or their interaction. The sample with the highest moisture content (i.e., 12%) milled at the lowest stone rotational speed (i.e., 120 RPM) showed the highest energy consumption (in addition to the highest milling time). The significant effect of moisture content can also be observed in this case, where chickpea with highest moisture content (i.e., 12%) have a more plastic behavior during milling, leading to a higher strain of the electric motor with the subsequent increase in energy consumptions [12,20].

Regarding average power, the two-way ANOVA highlighted individual main effect for stone rotational speed ($p < 0.001$) but not for moisture content or the factor interaction. As a result, average power significantly increases as the stone rotational speed increases. Tukey HSD test highlighted a significantly lower average power in the samples milled at the lowest stone rotational speed (i.e., 120 RPM). Since average power is the ratio between total work and the time for which the work is performed, and, moreover, given that the work has the dimensions of an energy (J), as the stone rotational speed of the mill increases, the energy transferred (and consequently the work transferred) over time increases, resulting in a rise in average power, a result consistent with those of other authors [21,22]. Finally, regarding specific milling energy, chickpea moisture content comes back to the fore. In particular, the two-way ANOVA found individual main effect for chickpea moisture content ($p < 0.001$), while this was not the case for stone rotational speed or factor interaction. Specific milling energy represents the energy required to produce 1 kg of chickpea flour. The results reported in Table 1 clearly highlight that specific milling energy significantly increases as chickpea moisture content increases. This result is consistent with milling time and with energy consumption, where dry raw materials are more brittle and less resistant than humid and conditioned ones, which show higher plasticity and are more difficult to be milled [12,20].

3.3. Particle Size Distribution

The results of particle size distribution are shown in Table 2.

Concerning the interval lower than 125 µm, the two-way ANOVA did not find any statistically significant differences. For the interval 125–250 µm, the results of the ANOVA found a significant individual effect of stone rotational speed ($p = 0.003$), while this was not the case for chickpea moisture content or their interaction. In particular, the sample with 10% moisture content milled at the highest rotational speed (i.e., 320 RPM), showed a significantly higher percentage of particles in the interval between 125 and 250 µm. Furthermore, these findings provide, for the first time in the literature, an optimal value of moisture content and milling speed for the milling process of chickpea. These results are supported by Vishwakarma et al. (2018) [23], which highlighted, in their literature review, that 10% moisture content is optimal for chickpea dehulling and milling. The authors also argued that 10% moisture content is optimal since it allows chickpea to have optimal mechanical and physical properties, thereby allowing the optimization of dehulling and milling unit operations. Unfortunately, Vishwakarma et al. (2018) [23] did not recommend any optimal milling speed for chickpea, highlighting the urgent need for this paper since the particle size distribution of flour significantly affects water absorption, dough rheological properties, and final bread characteristics.

Table 2. Results of flour particle size distribution expressed as the mean of three replicates ± SD. Letters represents statistically significant differences reported using the Tukey HSD post hoc test for stone rotational speed (a, b, c) and for chickpea moisture content (x, y, z). Columns without letters are not significantly different.

Sample	<125 µm (%)	125–250 µm (%)	250–400 µm (%)	400–600 µm (%)	>600 µm (%)
U 8%, speed 120 RPM	8.67 ± 7.51	25.00 ± 2.00 ^{a}	31.67 ± 4.04	28.33 ± 5.13 ^{ax}	6.33 ± 0.58 ^{ax}
U 8%, speed 220 RPM	8.67 ± 7.57	30.83 ± 4.65 ^{ab}	34.17 ± 2.25	21.83 ± 10.15 ^{ax}	4.50 ± 0.50 ^{by}
U 8%, speed 320 RPM	13.00 ± 8.72	33.00 ± 4.00 ^{ab}	34.00 ± 6.93	16.67 ± 5.51 ^{ax}	3.33 ± 0.58 ^{cz}
U 10%, speed 120 RPM	14.67 ± 4.16	27.67 ± 3.21 ^{a}	29.67 ± 3.51	23.00 ± 7.00 ^{ax}	5.00 ± 1.00 ^{ax}
U 10%, speed 220 RPM	13.67 ± 4.51	34.00 ± 6.00 ^{ab}	32.67 ± 2.89	15.33 ± 3.06 ^{ax}	4.33 ± 1.15 ^{by}
U 10%, speed 320 RPM	17.67 ± 7.51	41.67 ± 4.04 ^{c}	28.67 ± 2.89	8.00 ± 3.61 ^{cz}	4.00 ± 1.73 ^{by}
U 12%, speed 120 RPM	13.33 ± 5.13	30.67 ± 6.81 ^{ab}	31.00 ± 2.65	18.33 ± 4.16 ^{ax}	6.67 ± 1.53 ^{ax}
U 12%, speed 220 RPM	15.00 ± 11.79	29.33 ± 7.09 ^{ab}	31.67 ± 5.51	17.33 ± 2.08 ^{ax}	6.67 ± 3.06 ^{ax}
U 12%, speed 320 RPM	16.67 ± 13.05	38.00 ± 7.00 ^{b}	27.33 ± 7.09	12.67 ± 3.06 ^{by}	5.33 ± 1.53 ^{ax}

With respect to the interval 250–400 µm, the two-way ANOVA did not find any statistically significant differences. In contrast to the latter result, for the interval 400–600 µm, the two-way ANOVA pointed out individual main effect for stone rotational speed (p = 0.002) and moisture content (p = 0.028) but not the factor interaction. Moreover, for the last interval (i.e., > of 600 µm), the same results were highlighted by the two-way ANOVA (individual main effect for stone rotational speed (p = 0.05) and moisture content (p = 0.04)). Firstly, it is possible to underline that as stone rotational speed increases, the percentage of particles included in the interval 400–600 µm and bigger than 600 µm significantly decreases. Secondly, as found for the interval 125–250 µm, the sample with 10% moisture content milled at the highest speed (i.e., 320 RPM) showed the best performance, highlighting the absolute lowest value of particles in the interval 400–600 µm. With respect to the optimal moisture content of 10%, the reasons are the same as reported for the interval 125–250 µm. Concerning the optimal speed of 320 RPM, no article in the literature provides any sort of recommendation regarding the optimal milling speed of chickpeas. However, the results are supported by the findings reported in Section 3.4 that found the highest damaged starch content in the sample with 10% moisture content milled at the highest speed (i.e., 320 RPM). Nevertheless, it seems that the aforementioned speed allowed to provide the optimal amount of energy in the best time frame, allowing the best pulverization of the milled sample.

3.4. Flour Characterization and Analysis

Table 3 summarizes the results of moisture content and stone rotational speed on chickpea flour composition.

Regarding starch, the two-way ANOVA found a significant individual effect of chickpea moisture content (p = 0.016), while this was not the case for stone rotational speed or their interaction. As shown in Table 3, the starch content of flour decreases as chickpea moisture content increases, consistent with the findings of Ye et al. (2018) [24] and Colussi et al. (2020) [25]. However, the most interesting result concerns damaged starch content. With respect to damaged starch, the results of the ANOVA found a significant individual effect of stone rotational speed (p = 0.006), while this was not the case for chickpea moisture content or their interaction. As highlighted in Table 3, damaged starch content increases as stone rotational speed increases. Moreover, the sample with 10% moisture content milled at the highest speed (i.e., 320 RPM) showed the maximal content of damaged starch. The latter result is consistent with Sections 3.2 and 3.3 and with those of other authors [22,26,27]. In particular, Loubes et al. (2022) [22], Trappey et al. (2015) [26], and Loubes et al. (2018) [27]

found a statistically significant increase in damaged starch content as milling speed and process energy increased. This is mainly due to the impact of the different forces involved in the milling process on starch integrity and structural properties; when starch is subjected to a progressive increase in milling speed and energy, the damaged starch content in chickpea flours significantly increased, leading to an improved starch pulverization at the highest milling speed (i.e., 320 RPM).

Table 3. Results of flour characterization and analysis expressed as the mean of three replicates ± SD. Letters represents statistically significant differences reported using the Tukey HSD post hoc test for stone rotational speed (a, b) and for chickpea moisture content (x, y). Columns without letters are not significantly different.

Sample	Starch (%)	Damaged Starch (%)	Protein (g/100 g)	Total Polyphenols (mg/kg)
U 8%, speed 120 RPM	41.00 ± 2.17 ^{x}	1.38 ± 0.28 ^{a}	20.93 ± 0.38 ^{x}	389.00 ± 15.10
U 8%, speed 220 RPM	40.07 ± 2.15 ^{x}	1.66 ± 0.28 ^{a}	20.07 ± 0.12 ^{y}	392.33 ± 10.02
U 8%, speed 320 RPM	40.47 ± 1.05 ^{x}	1.89 ± 0.38 ^{a}	20.93 ± 0.40 ^{x}	427.33 ± 28.02
U 10%, speed 120 RPM	38.87 ± 2.15 ^{x}	1.35 ± 0.43 ^{a}	19.93 ± 0.65 ^{y}	395.67 ± 26.10
U 10%, speed 220 RPM	40.33 ± 1.45 ^{x}	1.57 ± 0.40 ^{a}	20.43 ± 0.38 ^{x}	411.67 ± 7.37
U 10%, speed 320 RPM	39.77 ± 1.12 ^{x}	1.94 ± 0.15 ^{b}	20.43 ± 0.25 ^{x}	415.00 ± 43.27
U 12%, speed 120 RPM	37.67 ± 1.52 ^{y}	1.16 ± 0.32 ^{a}	19.70 ± 0.40 ^{y}	474.33 ± 142.38
U 12%, speed 220 RPM	36.90 ± 2.69 ^{y}	1.30 ± 0.35 ^{a}	19.73 ± 0.98 ^{y}	389.67 ± 20.50
U 12%, speed 320 RPM	38.23 ± 2.67 ^{y}	1.78 ± 0.31 ^{a}	19.43 ± 0.86 ^{y}	393.00 ± 7.94

Concerning protein content, the two-way ANOVA found a significant individual effect of chickpea moisture content (p = 0.004). This was not the case for stone rotational speed or the factor interaction. In particular, Tukey HSD test highlighted a significantly lower protein content in samples with 12% moisture content compared to samples with 8% moisture content. The explanation of this result is probably related to the fact that when moisture content increases, energy consumption and specific milling energy increases, due to the increased plastic behavior of chickpea, which became harder to mill. Consequently, as highlighted in Table 1, the increase in temperature (ΔT) in the samples with 12% moisture content appears higher than the samples with 8% moisture content; as a result, when moisture content increases, energy consumptions, strain, and flour temperature increases, with subsequent protein denaturation. Finally, concerning the total polyphenols content, the two-way ANOVA did not find any statistically significant differences.

3.5. Correlation Analysis

The results of correlation analysis are summarized in Table 4.

Table 4. Results of correlation analysis performed using the Pearson Correlation Coefficient. Significance of correlation coefficients was tested using Bonferroni test.

Pearson Correlation Matrix		
	Chickpea Moisture Content	**Stone Rotational Speed**
Starch (%)	−0.57	0.06
Damaged starch (%)	−0.25	0.62
Protein (g/100g)	−0.61	0.05
Polyphenols (mg/kg)	0.13	−0.06
Flour yield (%)	−0.09	0.19
Temperature increase (°C) (DT)	0.05	0.67
Energy consumption (kWh)	0.74	−0.04
Average power (kW)	0.14	0.92
Specific milling energy (kJ/kg)	0.71	−0.05

As reported in Table 4, starch content shows a negative correlation (R = 0.57 (p = 0.046)) with chickpea moisture content. This is consistent with the results of the ANOVA. In particular, as shown in Table 3, the starch content of flour decreases as chickpea moisture content increases, consistent with the findings of Ye et al. (2018) [24] and Colussi et al. (2020) [25]. With respect to damaged starch, a good positive correlation has been found with stone rotational speed (R = 0.62 (p = 0.013)). Once again, this is consistent with the results of the ANOVA; more precisely, as highlighted in Table 3, damaged starch content increases as stone rotational speed increases, reaching its highest content in the sample with 10% moisture content milled at the highest speed (i.e., 320 RPM).

Furthermore, Pearson Correlation analysis shows a negative correlation between protein content and chickpea moisture content (R = 0.61 (p = 0.017)). This is confirmed by ANOVA. In particular, as highlighted in Section 3.4, when moisture content increases, energy consumptions, strain, and flour temperature increases, with subsequent protein denaturation. According to correlation analysis results, temperature increase displays a good positive correlation with stone rotational speed (R = 0.67 (p = 0.003)). Consistent with ANOVA results, chickpea flour temperature increases as stone rotation speed increases. With respect to energy consumptions, the correlation analysis found a strong positive correlation with chickpea moisture content (R = 0.74 (p < 0.001)). As highlighted in Section 3.2, the sample with the highest moisture content (i.e., 12%) showed the highest energy consumption and the highest milling time. The significant effect of moisture content can also be observed in this case, where chickpeas with the highest moisture content (i.e., 12%) have a more plastic behavior during milling, leading to a higher strain of the electric motor with the subsequent increase in energy consumptions [12,20].

Concerning average power, the correlation analysis highlighted a strong positive correlation with stone rotational speed (R = 0.92 (p = < 0.001)). Furthermore, these results are consistent with the ANOVA. In particular, average power increases as the stone rotational speed increases. Finally, Pearson Correlation analysis found a good correlation between specific milling energy and chickpea moisture content (R = 0.71 (p = 0.001)). Specific milling energy represents the energy required to produce 1 kg of chickpea flour. The results reported in Tables 1 and 4 highlight that specific milling energy significantly increases as chickpea moisture content increases. This result is consistent with the ANOVA results. The explanation of these results is related to the fact that dry raw materials are more brittle and less resistant than more humid and conditioned ones, which show higher plasticity and are more difficult to mill [12,20].

4. Conclusions

Our results highlight that moisture content and stone rotational speed have statistically significant effects on milling operative parameters, on flour particle size, and, finally, on chickpea flour composition. In particular, stone rotational speed and chickpea moisture content affected almost all the tested variables. As stone rotational speed increases, flour temperature (ΔT), average power, and damaged starch content significantly increases. On the other hand, milling time significantly decreases as stone rotational speed increases. With respect to moisture content, the results found that as moisture content increases, energy consumption and specific milling energy increases. On the contrary, starch and protein content of chickpea flour significantly decreases as moisture content increases.

These findings clearly highlight that stone rotational speed and moisture content are powerful tools that allow the utilization of the milling process to modulate the characteristics of the obtained flours. Moreover, the results of this study recommend, for the first time in the literature, optimal values of moisture content and milling speed of chickpea. In particular, the results suggest that a chickpea moisture content of 10% and a milling speed of 320 RPM allow to reduce milling time, optimize particle size distribution of chickpea flour (significantly increasing the percentage of particles in the interval between 125 and 250 µm, reaching desirable particle size distribution), reduce specific milling energy, and, finally, increase the damaged starch content in chickpea flours. An optimal content of damaged starch is essential for the food industry as it increases flour water absorption and the availability of simple sugars improving the overall rheological properties of doughs. In conclusion, milling chickpeas with a moisture content of 10% at a milling speed of 320 RPM seems to be the best compromise between milling operative parameters, particle size, and chickpea flour composition.

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