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# Chia (*Salvia hispanica* L.) oil extraction: Study of processing parameters

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ABSTRACT

The processing parameters related with chia oil extraction employing screw press have not been studied yet. A Box–Behnken experimental design was used to study the optimization process by response surface analysis. The independent variables considered were seed moisture content, restriction die, screw press speed and barrel temperature, while the response variables measured were oil yield, fines content in oil and oil quality (acidity, peroxide index, $K_{232}$, $K_{270}$, values, antioxidant activity and total tocopherol content). Since chemical quality data of chia seeds oil pressed at different conditions was not affected, the response was optimize to maximize oil yield. The results suggested that 0.113 g/g dry solids (0.101 g/g seed), 6 mm restriction die, 20 rpm screw press speed and 30 °C barrel temperature were the best processing combination to maximize oil yield.



## 1. Introduction

Nowadays, consumers' tendency on choosing food is more associated to health and wellness. This situation can clearly be seen on market with the supply of products distinguished by their content on omega (ω)-3, antioxidants, dietary fiber, and other components that usual consumers are learning to recognize as a healthy contribution.

*Salvia hispanica* L. or chia is native from the region that extended from west central Mexico to northern Guatemala. Its seeds were widely used by Aztecan tribes, principally as food and also as medicine and for paint manufacturing. Chia is considered an annual crop, of summer, that belongs to the Labiatae (Coates & Ayerza, 1996). At present chia is grown mainly in Mexico, Bolivia, Ecuador and Guatemala. Since 1991 this crop has been successfully developed in Argentina, mostly in the north of the country in the provinces of Salta and Jujuy where, nowadays, it has turned into a very important economic activity.

Chia crop has been studied principally because of its oil quality. The seed contains between 0.25 and 0.38 g oil/g seed, where the major constituents are triglycerides, in which polyunsaturated fatty acids (PUFAs, α-linolenic and linoleic acids) are present in high amounts (Ayerza, 1995; Ixtaina et al., 2011; Palma & Dondem, 1947). (ω)-3 fatty acids play a very essential role in physiology, especially during fetal and infant growth (Bowen & Clandinin, 2005) and in the prevention of cardiovascular diseases, being antithrombotic, antiinflammatory, antiarrythmic and favoring plaque stabilization (Galli & Marangoni, 2006). It also has high level of proteins (0.19–0.23 g/g seed), antioxidants, tocopherols (238–427 mg/kg) and polyphenols, being the major phenolic compounds chlorogenic and caffeic acids, followed by myricetin, quercetin and kaempferol (Ixtaina et al., 2011).

Chia oil can be obtained by different methods such as solvent extraction, by pressing and using supercritical $CO_2$. The experimental results show that the oil yield was much lower in pressing than in solvent extraction and the composition of minor constituents of chia seed oils, such as tocopherols and polyphenols, were influenced by the extraction process. For supercritical $CO_2$ extraction, time and pressure had the greatest impact on oil yield (Ixtaina et al., 2010, 2011; Rocha Uribe, Novelo Perez, Castillo Kauil, Rosado Rubio & Alcocer 2011).

A major goal in chia oil production is to find an appropriate method to recover it from the seeds preserving oil quality. It is desirable to employ simple extraction processes, which implementation, operation and control as well as investment may be accessible to local producers. In recent years, there has been a resurgence of interest in the use of continuous, mechanical screw-

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presses to recover oil from oilseeds. Although screw pressing will not extensively replace solvent extraction in commodity oilseeds because it recovers a lower proportion of oil; in the case of new specialty edible oils, screw pressing provides a simple and reliable method of processing small batches of seed (Martínez, Mattea, & Maestri, 2008; Singh, Wiesenborn, Tostenson, & Kangas, 2002; Wiesenborn, Doddapaneni, Tostenson, & Kangas, 2001; Zengh, Wiesenborn, Tostenson, & Kangas, 2003).

To date, there is little information about influence of the extraction parameters as seed moisture content, temperature, and screw press conditions on oil yield and quality (Ixtaina et al., 2011).

Based on the above exposed, the aim of this work was to evaluate the effect of processing parameters of chia seeds on oil yield and quality during screw pressing.

## 2. Materials and methods

### 2.1. Materials

Chia seeds (*S. hispanica* L.) coming from the province of Salta, Argentina (Nutracéutica Sturla SRL) were cleaned, manually classified, packed in polypropylene bags and stored at 5 °C until further use. 2,2 diphenyl-1-picrylhydrazyl (DPPH) and bovine albumin were purchased from Sigma Aldrich. Spectrophotometric grade cyclohexane (Sintorgan, Argentina) was used for $K_{232}$, $K_{270}$ analysis. Other reagents were analytical or HPLC grade.

### 2.2. Methods

#### 2.2.1. Chia seed composition

Samples were analyzed according to standards AACC (AACC, 2003) and AOCS (AOCS, 2009) for total oil content, fatty acid profile, total protein, total carbohydrates and ash.

#### 2.2.2. Seed hydration

The initial moisture content was determined according AOCS method (AOCS, 2009). In order to achieve the initial moisture proposed in the experimental design, seeds were hydrated according to the methodology proposed by Singh and Bargale (2000); the water was sprinkled onto the material. Seeds were then packed in air-tight containers and stored for 48 h for equilibration. The containers were shaken at regular intervals to distribute moisture uniformly throughout the sample.

#### 2.2.3. Screw press extraction

The oil extraction was carried out in a single step with a Komet screw press, pilot plant scale type (Model CA 59 G, IBG Monforts, Germany). The moisture content of the seeds varied between 0.136 and 0.250 g/g dry solids (12–20 g/100 g seed) and the pressing temperature was between 30 and 70 °C, which were reached by attaching an electrical resistance-heating ring around the press barrel. The screw speed had a minimum of 20 rpm and a maximum of 40 rpm. The minimum and maximum restriction die used were 6 and 10 mm, respectively.

Both, the temperature of oil and the temperature of outgoing material (residue or cake) were constantly monitored with a digital thermometer inserted into the restriction die.

#### 2.2.4. Oil yield

The oil yield (OY) was calculated considering the initial oil content in the incoming material and the residual oil content in the cake. Both were determined according to AOCS (2009). OY was expressed as g extracted oil/g of total oil present in the incoming material × 100 (g/100 g oil).

#### 2.2.5. Amount of fines in oil

The screw-pressed oil samples were centrifuged at 11,000 g for 30 min. The precipitated solids were recovered, washed with cyclohexane, dried and weighed. Solid content was expressed as g solids/100 g extract (oil + solid).

#### 2.2.6. Oil analysis

The values of acidity, peroxide index (PI) specific extinction coefficients $K_{232}$ and $K_{270}$ were determined according to standard methods of AOCS (AOCS, 2009). The fatty acids profile was analyzed by gas chromatography (GC) using the methodology proposed by Martínez, Mattea, & Maestri (2006). Total tocopherols (TT) were determined by high pressure liquid chromatography (HPLC) according to Pocklington and Dieffenbacher (1988). The antiradical activity (AA) was measured according to Martínez & Maestri, 2008. An aliquot (100 mg) of oil was dissolved in 1 mL toluene and then 3.9 mL of a DPPH radical solution (0.004 g DPPH·r/100 mL of toluene) were added. The absorbance (515 nm) values were measured after 30 min of incubation. The antiradical activity was expressed as remaining radical DPPH percentage (DPPH·r percentage).

#### 2.2.7. Experimental design and response surface analysis

Experiments were planned applying a Box–Behnken design (Montgomery, 2005). Three different levels were used for each of the following factors: seed moisture ($X_1$); restriction die ($X_2$); pressing temperature ($X_3$), pressing speed ($X_4$). The evaluated responses were oil yield ($Y_1$) and quality of oil obtained: peroxide index ($Y_2$), acidity ($Y_3$), $K_{232}$ ($Y_4$), $K_{270}$ ($Y_5$), total tocopherol ($Y_6$) and antioxidant activity ($Y_7$). Quadratic polynomials were fitted to express the responses ($Y_n$) as a function of factors (Eq. (1)); where $R$ is the response, $\beta_0$ is the constant term, $\beta_i$ represents the coefficients of the linear parameters, $X_i$ represents the factors, $\beta_{ii}$ represents the coefficients of the quadratic parameter, $\beta_{ij}$ represents the coefficients of the interaction parameters and $\varepsilon$ is the random error.

The results were analyzed by a multiple regression method. The experimental results were applied to obtain the regression models. Quality of the model fitness was evaluated by ANOVA (Statgraphic Plus software v 5.1, USA). The fit of model to the experimental data was given by the coefficient of determination, $R^2$, which explains the extent of the variance in a modeled variable that can be explained with the model. Only models with high coefficient of determination were included in this study. Multiple regression equations included only significant coefficients ($p < 0.05$). Three-dimensional response surface graphics were generated for each response variable.

$$Y = \beta_0 + \sum_{i=1}^{4} \beta_i X_i + \sum_{i=1}^{4} \beta_{ii} X_i^2 + \sum_{i=1}^{3} \sum_{j=1}^{4} \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

All determinations were performed at least in duplicate, randomly, and replicas of the central point were done to allow estimation of pure error as square sums. Two different designs were carried out, the first one as exploratory (preliminary essays) and the second one, to define the optimal of design factors. Statistical analysis of data was performed using Statgraphic Plus software (v 5.1, USA).

## 3. Results and discussion

### 3.1. Characteristics of vegetable material

Seed composition is shown in Table 1. The oil content was consistent with reported values (Ayerza, 1995; Ixtaina et al., 2011). Abundance order of fatty acids was as follows: α-Linolenic acid

**Table 1**
Chia seed composition.

| Parameter | Value[a] |
|---|---|
| Moisture content (g/g dry solids) | 0.072 ± 0.001 |
| Total protein (g/g seed) | 0.218 ± 0.006 |
| Ash (g/g seed) | 0.044 ± 0.001 |
| Carbohydrates (g/g seed)[b] | 0.334 |
| Oil content (g/g seed) | 0.317 ± 0.004 |
| Fatty acid distribution (relative abundance) | |
| Palmitic acid (16:0) | 7.3 ± 0.2 |
| Stearic acid (18:0) | 2.8 ± 0.2 |
| Oleic acid (18:1) | 7.4 ± 0.8 |
| Linoleic acid (18:2) | 22.0 ± 0.1 |
| Linolenic acid (18:3) | 60.5 ± 1.2 |

[a] Mean ± standard deviation ($n = 3$).
[b] By difference.

(C18:3) gt; linoleic acid (C18:2) gt; oleic acid (C18:1) ≈ palmitic acid (C16:0) gt; stearic acid (C18:0).

### 3.2. Exploratory test

In a first stage, an experimental design of 28 treatments was carried out (4 central points) using the described factors and levels (Table 2). Fig. 1 shows the most relevant effects on oil yield. Only seed moisture and pressing speed showed *p*-values lower than the level of significance ($\alpha = 0.05$). Pressing temperature and restriction die had no significant influence ($p < 0.05$). Oil yield values were between 3.9 and 48.0 g/100 g oil. Treatments with initial moisture content of 0.190 g/g dry solids showed the highest variability (16.0–44.4 g/100 g oil, Table 2). The amount of solids recovered from oil was not significantly affected by design variables. The previous hydration of seeds did not increase the oil acidity, which ranged between 0.51 and 0.69 (g oleic acid/g oil). The increase of seed moisture and pressing temperature affected negatively the peroxide index but chemical quality of oils obtained in all treatments was acceptable (Codex, 2008). This parameter varied between 0.69 and 2.67 (meq/kg oil). Similar results were reported by Ayerza & Coates (2009). Specific extinction coefficients $K_{232}$ and $K_{270}$ values were within: 1.35–1.83 and 0.40–0.67, respectively. The oils obtained showed similar tocopherol content (396–444 mg/kg) compared with data informed by Ixtaina et al. (2011). The DPPH assay measures the ability of compound to transform labile H-atoms to radicals and is the most common method of antioxidant evaluation. The abstraction of hydrogen of this stable free radical is known to lead to bleaching with a maximum absorption band at 515 nm (Zhang et al. 2010). Antiradical activity varied between 59 and 63 percentage activity which can be attributed to the tocopherol (TT) and polyphenol content in chia oil (Ixtaina et al., 2011).

The seed moisture, speed and temperature of pressing and the restriction die affected oil yield and peroxide index parameters (Table 2).

Water addition before pressing causes an expansion and breaking of cell structure that makes it more permeable and improves oil yield. It is known that moisture increases plasticity of seeds material, contributes to press feeding owing to its effects as barrel lubricant. However, high seed moisture contents resulted in poor oil recoveries because of insufficient friction during pressing. This effect may be due to the formation of an external gelatinous structure with water-holding properties. These observations are consistent with the fact that seed hydration affects the mucilage structure characteristic of chia (Singh & Bargale, 2000; Vázquez-Ovando, Rosado-Rubio, Chel-Guerrero, & Betancur-Ancona, 2009). Hence optimal moisture content should be determinate for each given oil seed (Li, Bellmer, & Brusewitz, 1999; Martínez et al., 2008; Singh & Bargale, 1990, 2000). In this study, pressing of chia seeds with a moisture content ranged between 0.190 and 0.250 g/g dry

**Table 2**
Box–Benkhen design. Effect of process variables on the yield of oil and their quality parameters.

| Assay | Factors[a] | | | | OY | PI | Ac | $K_{232}$ | $K_{270}$ | AA | TT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | $X_4$ | | | | | | | |
| 1 | 0.136 | 8 | 30 | 30 | 45.3 ± 0.42 | 0.68 ± 0.08 | 0.55 ± 0.01 | 1.36 ± 0.11 | 0.67 ± 0.01 | 58.7 ± 1.21 | 410 ± 3.54 |
| 2 | 0.136 | 8 | 50 | 20 | 46.7 ± 0.21 | 1.22 ± 0.14 | 0.57 ± 0.02 | 1.38 ± 0.13 | 0.64 ± 0.02 | 60.1 ± 1.35 | 419 ± 2.12 |
| 3 | 0.136 | 8 | 50 | 40 | 34.3 ± 0.35 | 0.99 ± 0.09 | 0.58 ± 0.04 | 1.36 ± 0.14 | 0.50 ± 0.04 | 59.6 ± 1.28 | 421 ± 5.60 |
| 4 | 0.136 | 10 | 50 | 30 | 41.9 ± 0.28 | 1.00 ± 0.02 | 0.59 ± 0.03 | 1.37 ± 0.15 | 0.50 ± 0.03 | 59.4 ± 1.35 | 402 ± 3.54 |
| 5 | 0.136 | 6 | 50 | 30 | 48.1 ± 0.35 | 1.40 ± 0.13 | 0.55 ± 0.05 | 1.35 ± 0.17 | 0.45 ± 0.07 | 61.2 ± 1.37 | 414 ± 4.28 |
| 6 | 0.136 | 8 | 70 | 30 | 33.0 ± 0.40 | 1.36 ± 0.13 | 0.59 ± 0.06 | 1.37 ± 0.12 | 0.58 ± 0.04 | 59.6 ± 1.28 | 413 ± 4.54 |
| 7 | 0.190 | 10 | 70 | 30 | 39.7 ± 0.21 | 0.99 ± 0.01 | 0.61 ± 0.07 | 1.35 ± 0.11 | 0.53 ± 0.02 | 58.9 ± 1.21 | 397 ± 2.83 |
| 8 | 0.190 | 6 | 70 | 30 | 44.4 ± 0.28 | 1.85 ± 0.20 | 0.58 ± 0.01 | 1.36 ± 0.13 | 0.47 ± 0.03 | 61.8 ± 1.28 | 398 ± 3.54 |
| 9 | 0.190 | 6 | 30 | 30 | 23.3 ± 0.35 | 1.34 ± 0.12 | 0.64 ± 0.03 | 1.40 ± 0.16 | 0.49 ± 0.05 | 62.0 ± 1.21 | 410 ± 5.83 |
| 10 | 0.190 | 10 | 30 | 30 | 19.4 ± 0.41 | 1.38 ± 0.13 | 0.63 ± 0.04 | 1.42 ± 0.13 | 0.46 ± 0.07 | 60.1 ± 1.49 | 444 ± 2.83 |
| 11 | 0.190 | 10 | 50 | 20 | 35.7 ± 0.21 | 1.44 ± 0.12 | 0.60 ± 0.03 | 1.44 ± 0.12 | 0.47 ± 0.03 | 59.4 ± 1.42 | 423 ± 3.55 |
| 12 | 0.190 | 10 | 50 | 40 | 16.0 ± 0.35 | 2.32 ± 0.23 | 0.70 ± 0.04 | 1.35 ± 0.13 | 0.51 ± 0.02 | 63.2 ± 1.35 | 415 ± 2.83 |
| 13 | 0.190 | 6 | 50 | 40 | 22.3 ± 0.42 | 1.85 ± 0.11 | 0.62 ± 0.03 | 1.46 ± 0.12 | 0.48 ± 0.06 | 61.0 ± 1.40 | 411 ± 3.70 |
| 14 | 0.190 | 6 | 50 | 20 | 42.2 ± 0.35 | 1.81 ± 0.22 | 0.61 ± 0.04 | 1.36 ± 0.14 | 0.46 ± 0.03 | 61.3 ± 1.35 | 417 ± 5.83 |
| 15 | 0.190 | 8 | 30 | 20 | 41.9 ± 0.31 | 0.95 ± 0.13 | 0.52 ± 0.05 | 1.40 ± 0.12 | 0.43 ± 0.02 | 59.5 ± 1.43 | 412 ± 3.54 |
| 16 | 0.190 | 8 | 30 | 40 | 23.3 ± 0.42 | 1.57 ± 0.12 | 0.67 ± 0.06 | 1.41 ± 0.13 | 0.45 ± 0.04 | 61.1 ± 1.42 | 396 ± 3.88 |
| 17[b] | 0.190 | 8 | 50 | 30 | 21.0 ± 0.34 | 1.32 ± 0.08 | 0.67 ± 0.02 | 1.47 ± 0.12 | 0.52 ± 0.03 | 61.3 ± 1.23 | 411 ± 2.92 |
| 18[b] | 0.190 | 8 | 50 | 30 | 20.7 ± 0.36 | 1.58 ± 0.11 | 0.65 ± 0.04 | 1.83 ± 0.17 | 0.40 ± 0.05 | 62.3 ± 1.48 | 414 ± 2.11 |
| 19[b] | 0.190 | 8 | 50 | 30 | 22.3 ± 0.29 | 1.71 ± 0.19 | 0.69 ± 0.01 | 1.47 ± 0.12 | 0.46 ± 0.01 | 61.8 ± 1.35 | 424 ± 3.15 |
| 20[b] | 0.190 | 8 | 50 | 30 | 21.8 ± 0.18 | 1.27 ± 0.09 | 0.66 ± 0.03 | 1.45 ± 0.16 | 0.48 ± 0.04 | 58.5 ± 1.28 | 421 ± 2.87 |
| 21 | 0.190 | 8 | 70 | 20 | 24.2 ± 0.42 | 1.28 ± 0.12 | 0.62 ± 0.04 | 1.39 ± 0.12 | 0.48 ± 0.03 | 60.3 ± 1.49 | 421 ± 3.54 |
| 22 | 0.190 | 8 | 70 | 40 | 20.5 ± 0.35 | 2.67 ± 0.22 | 0.69 ± 0.06 | 1.36 ± 0.13 | 0.49 ± 0.04 | 61.3 ± 1.52 | 419 ± 6.01 |
| 23 | 0.250 | 8 | 30 | 30 | 19.3 ± 0.42 | 1.14 ± 0.12 | 0.60 ± 0.04 | 1.45 ± 0.16 | 0.46 ± 0.03 | 61.9 ± 1.35 | 416 ± 3.54 |
| 24 | 0.250 | 8 | 50 | 40 | 16.9 ± 0.30 | 0.26 ± 0.07 | 0.62 ± 0.03 | 1.37 ± 0.13 | 0.55 ± 0.04 | 62.8 ± 1.42 | 413 ± 4.95 |
| 25 | 0.250 | 8 | 50 | 20 | 29.0 ± 0.42 | 0.14 ± 0.03 | 0.51 ± 0.02 | 1.46 ± 0.11 | 0.46 ± 0.03 | 61.4 ± 1.45 | 407 ± 3.90 |
| 26 | 0.250 | 6 | 50 | 30 | 3.9 ± 0.21 | 1.73 ± 0.18 | 0.58 ± 0.03 | 1.41 ± 0.14 | 0.51 ± 0.07 | 62.8 ± 1.28 | 413 ± 4.95 |
| 27 | 0.250 | 10 | 50 | 30 | 12.8 ± 0.43 | 0.93 ± 0.04 | 0.64 ± 0.05 | 1.36 ± 0.13 | 0.55 ± 0.06 | 61.7 ± 1.40 | 416 ± 5.02 |
| 28 | 0.250 | 8 | 70 | 30 | 12.9 ± 0.35 | 1.07 ± 0.04 | 0.61 ± 0.04 | 1.51 ± 0.11 | 0.47 ± 0.03 | 61.3 ± 1.49 | 416 ± 4.24 |

Mean ± standard deviation ($n = 2$).
[a] $X_1$: seed moisture (g/g dry solids), $X_2$: restriction die (mm), $X_3$: pressing temperature (°C), $X_4$: pressing speed (rpm). OY: Oil yield (g/100 g oil), PI: peroxide index (meq/kg oil), Ac: Acidity (g oleic acid/g oil), AA: antiradical activity (percentage activity), TT: total tocopherol (mg/kg).
[b] Central point.

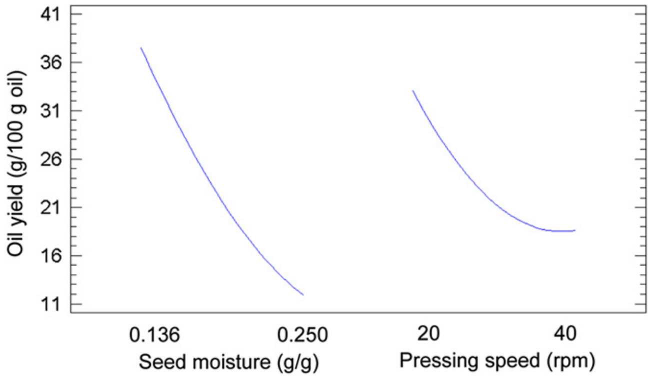


**Fig. 1.** Main significant effects on oil yield in the exploratory test.

solids, formed a plastic mass that diverted through the barrel openings affecting oil recovery.

### 3.3. Effect of process variables on oil yield

The experimental design factors had slight or non influence on the chemical quality of the oils produced by different treatments (Table 2); only the response variable oil yield was significantly affected by the different combinations of design variables. Based on the results of the exploratory test, a new experimental design was developed considering seed moisture ($X_1$), restriction die ($X_2$), and pressing speed ($X_3$) as incoming factors in order to improve oil yield ($Y$). The pressing temperature factor remained constant (30 °C) since the results of analysis of the variance in the exploratory test showed no significant influence on oil yield. The new Box–Behnken design studied the effect of those 3 incoming factors in 16 experiments (4 central points). The experimental design and the response variable considered are shown in Table 3.

The statistical analysis showed that seed moisture, restriction die, and pressing speed significantly affected oil yield ($p < 0.05$).

Equation of the fitted model is:

$$\text{Oil yield} = 448.42 - 5458.18X_1 - 2.25X_2 - 0.45X_3 + 20272.8X_1^2 - 0.89X_2^2 + 0.31X_2X_3 - 0.034X_3^2 \quad (2)$$

The coefficient of determination of the model was able to explain 95.5 percentage of the data variability. The seed moisture, restriction die and pressing speed had negative linear effect on the oil yield while the seed moisture and restriction die had positive and negative quadratic effect. A positive cross effect was observed between restriction die and pressing speed.

The decrease of seed moisture resulted in an increase of oil yield and the highest values of oil yield were obtained with the lowest values of seed moisture (Fig. 2). A similar trend was reported for crambe seed (in the moisture content range of 0.092 to 0.036 g/g dry solids), for flaked and cooked soybean (in the moisture content range of 0.081–0.136 g/g dry solids) and uncooked canola seed (in the moisture content range of 0.060–0.100 g/g dry solids). However, other reports showed a maximum in oil yield at 0.075 g/g dry solids for uncooked flaxseed (in the moisture content range of 0.053–0.124 g/g dry solids) and at 0.111 g/g dry solids for uncooked rapeseed (in the moisture content range of 0.053–0.124 g/g dry solids); recovery decreased with further decrease in moisture content in those studies (Singh et al., 2002). In the present study, the pressing could not be carried out successfully below a moisture content of 0.111 g/g dry solids due to plugging of the screw press.

Reducing the restriction and pressing speed increased the compression exerted on the seeds and the dwell time of the material inside of the press, with a consequent increased of the oil extracted. This combination produced the highest values of oil yield (Fig. 2).

The results showed a significantly higher oil yield (57.2–81.1 g/100 g oil) than those obtained in the exploratory tests. The maximum amount of oil extracted in the essays was obtained with treatment number 13 and was of 81.1 g/100 g oil; due to low moisture content of the seed no plastic mass inside the press was formed.

The combination of factor levels that suggested a maximum on oil yield within the experimental values was 0.113 g/g dry solids seed moisture; 20 rpm pressing speed and 6 mm restriction die

**Table 3**
Box–Behnken design. Effect of process variables on the yield of oil.

| Treatment | $X_1$ | $X_2$ | $X_3$ | OY |
|---|---|---|---|---|
| 1 | 0.111 | 8 | 40 | 73.6 ± 0.3 |
| 2 | 0.111 | 8 | 20 | 76.2 ± 0.5 |
| 3 | 0.111 | 6 | 30 | 78.6 ± 1.0 |
| 4 | 0.111 | 10 | 30 | 70.8 ± 0.9 |
| 5 | 0.136 | 6 | 30 | 72.2 ± 0.3 |
| 6 | 0.136 | 10 | 30 | 68.6 ± 1.0 |
| 7 | 0.136 | 8 | 20 | 72.4 ± 0.4 |
| 8 | 0.136 | 8 | 40 | 68.8 ± 0.9 |
| 9[a] | 0.124 | 8 | 30 | 73.7 ± 0.4 |
| 10[a] | 0.124 | 8 | 30 | 72.1 ± 0.5 |
| 11[a] | 0.124 | 8 | 30 | 73.1 ± 0.2 |
| 12[a] | 0.124 | 8 | 30 | 72.5 ± 0.8 |
| 13 | 0.124 | 6 | 20 | 81.1 ± 0.3 |
| 14 | 0.124 | 6 | 40 | 62.5 ± 0.7 |
| 15 | 0.124 | 10 | 20 | 57.2 ± 0.7 |
| 16 | 0.124 | 10 | 40 | 63.0 ± 0.4 |

Mean ± standard deviation ($n = 2$).
$X_1$: seed moisture (g/g dry solids), $X_2$: restriction die (mm), $X_3$: pressing speed (rpm); OY: Oil yield (g/100 g oil).
[a] Central point.

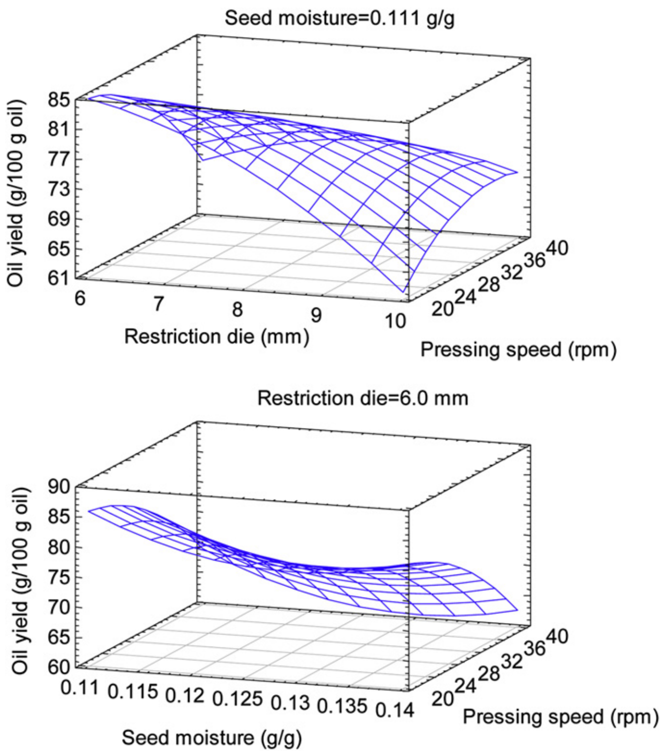


**Fig. 2.** Effects of seed moisture content, screw press speed and restriction die on oil yield.

**Table 4**
Chemical parameters of oil extracted under conditions of optimal model point.

| Oil chemical quality[a] | |
|---|---|
| Acidity[b] | 0.49 ± 0.01 |
| PI[c] | 0.70 ± 0.03 |
| $K_{232}$ | 1.43 ± 0.01 |
| $K_{270}$ | 0.22 ± 0.01 |
| AA[d] | 49.8 ± 0.3 |
| TT[e] | 502 ± 2 |

[a] Mean ± standard deviation ($n = 4$).
[b] Acidity (g oleic acid/g oil).
[c] IP (peroxide index, meq/kg oil).
[d] AA (antiradical activity, percentage activity).
[e] TT (total tocopherol, mg/kg).

of the press. This combination of factors was conducted following the procedures mentioned. The results showed that no significant differences were found between the estimated value by the model (83.8 g/100 g oil) and the experimental observed value (82.2 ± 1.8 g/100 g oil) for oil yield which suggests a good fit of the model to experimental data.

Chemical parameters of the oil obtained according to the optimized response are shown in Table 4. As described above, the oil chemical quality was not adversely affected by the extraction process.

## 4. Conclusions

The Box–Behnken design allowed determining the optimal combination of variables for the optimization of the process for extracting oil from chia seed by screw press at pilot scale. Chemical quality of oil samples obtained did not show oxidative and/or hydrolytic damage. Oil yield from chia seeds by pressing can be enhanced by adjusting moisture content 0.113 g/g dry solids (0.101 g/g seed), 6 mm restriction die, 20 rpm screw press speed and 30 °C barrel temperature to obtain an oil yield value of 82.2 g/100 g oil.

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