LWT - Food Science and Technology 147 (2021) 111580

Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

Production of extruded-cooked lentil flours at industrial level: Effect of processing conditions on starch gelatinization, dough rheological properties and techno-functional parameters

Antonella Pasqualone [a,*], Michela Costantini [a], Rossella Labarbuta [b], Carmine Summo [a]

[a] *Department of Soil, Plant and Food Sciences, University of Bari Aldo Moro, Via Amendola, 165/A, Bari, 70126, Italy*
[b] *Andriani Spa, Via Nicolò Copernico, Gravina in Puglia, 70024, Italy*

ARTICLE INFO

Keywords:
Extrusion-cooking
Lentil
Mixolab
Viscoamylograph
Pasting properties

ABSTRACT

The aim of this work was to identify the effect of two different extrusion-cooking (E-C) conditions, milder and more severe, on starch gelatinization, dough rheological properties and techno-functional parameters of lentil flour (*Lens culinaris* Medik.). Extruded flours were obtained at 100 °C die temperature, with a screw speed of 220 rpm (EF1) and at 115 °C, 230 rpm (EF2), in an industrial plant. The E-C increased the viscoamylograph initial viscosity compared with native flour (NF), with a significantly higher value ($p < 0.05$) in EF1 (69.3 ± 4.1 Brabender Units, BU) than EF2 (59.1 ± 3.1 BU). The extruded flours also showed a lower degree of starch retrogradation than NF (cooling maximum viscosity = 201.3 ± 6.4 BU in EF1, 194.1 ± 9.2 BU in EF2 and 433.5 ± 8.5 BU in NF). The E-C markedly increased the Mixolab maximum consistency (with EF1 reaching 1.77 ± 0.04 Nm) compared with NF. The techno-functional parameters significantly improved, compared with NF, with an increase in water absorption index (higher in EF1 than in EF2) and oil absorption capacity (higher in EF2 than in EF1), and a decrease in bulk density. Therefore, by conveniently modulating the industrial processing conditions, lentil flour can become a valuable ingredient for several food applications.

1. Introduction

Lentil (*Lens culinaris* Medik.) is a widely cultivated leguminous food crop, commonly consumed worldwide, particularly in the Mediterranean area (FAOSTAT, 2018). The highest consumption occurs in the Middle East and North Africa, where it reaches 2.3 kg/person/year (Nedumaran et al., 2015). As other pulses, lentils are an excellent source of energy, proteins, dietary fibers, and micronutrients (De Ron, 2015). In particular, the protein content of lentil is notably high, varying from 20 to 24 g 100 g^{-1} (De Angelis et al., 2020). Lentils are mostly consumed as grain, but recently the addition of lentil flour to snack-type foods (Morales et al., 2015) and bread (Marchini et al., 2021; Turfani, Narducci, Durazzo, Galli, & Carcea, 2017) has been proposed. Lentil flour is also suitable for producing gluten-free foods, but its poor rheological properties should be compensated by adding hydrocolloids and/or enzymes to improve dough stability and volume (Naqash, Gani, Gani, & Masoodi, 2017). Alternatively, the flour can be hydrothermally treated to induce starch gelatinization and to increase its viscosity when rehydrated, which is essential to entrap air bubbles in gluten-free dough (Naqash et al., 2017).

Widely applied to produce ready-to-eat foods, extrusion-cooking (E-C) is used also to obtain pregelatinized flours. This processing technology is characterized by high productivity, low operating costs, high energy efficiency and short processing times (Ganjyal, 2020). The raw materials, conditioned at a certain moisture content, are fed into the heated barrel of the extruder-cooker, where are subjected to thermal stress and to the mechanical action of a rotating screw. E-C has multiple biochemical effects, such as starch gelatinization, protein denaturation, and increase of soluble dietary fiber (Morales et al., 2015). In addition, this technology reduces the anti-nutritional compounds, such as trypsin inhibitors, phytic acid, and tannins, known to affect the digestibility of pulses, including lentils (Ciudad-Mulero et al., 2020; Rathod & Annapure, 2016). Therefore, the E-C of pulses has emerged, particularly in the last years (Pasqualone, Costantini, Coldea, & Summo, 2020), because E-C can improve the product quality compared with traditional technologies (Ganjyal, 2020).

Most of the world production of lentil is sold as it is, without adding value (Luo et al., 2020). The food industries are therefore interested in

---

* Corresponding author.
E-mail address: antonella.pasqualone@uniba.it (A. Pasqualone).

https://doi.org/10.1016/j.lwt.2021.111580
Received 21 December 2020; Received in revised form 20 April 2021; Accepted 21 April 2021

the formulation of extruded-cooked lentil-based ingredients. New lentil-based products could satisfy the increasing demand of vegan consumers and, more generally, of consumers who are aware of the importance of a healthy diet.

The E-C of lentil has been proposed by several authors, who compared the effect of different processing conditions on the properties of the extruded product (Ciudad-Mulero et al., 2020; Ek, Gu, & Ganjyal, 2021; Ghumman, Kaur, Singh, & Singh, 2016; Guillermic et al., 2021; Luo et al., 2020; Rathod & Annapure, 2016). These studies evaluated the effect of E-C on protein digestibility (Ghumman et al., 2016), anti-nutritional compounds, phytochemicals, quality indices (Ciudad-Mulero et al., 2020; Ek et al., 2021; Rathod & Annapure, 2016), and microstructure (Guillermic et al., 2021; Luo et al., 2020), but did not consider the pasting characteristics and the dough mixing properties, which are also essential to provide the best food application of extruded flours. However, these studies were set up at laboratory level and, to translate the results to industrial conditions, would require a scale-up which, instead, is still absent in the available literature.

As with other processes of food industry, the scale-up of E-C is affected by several difficulties. The most critical issue is the decrease of the surface/volume ratio on scaling-up, which limits the heat transfer. The temperature differences set in lab scale equipment correspond to smaller temperature gradients and heat fluxes in larger industrial plants, involving the need to accurately redefine the entire process (Ganjyal, 2020).

Therefore, this work aims to identify the effect of two different E-C conditions on starch gelatinization, dough mixing properties and techno-functional parameters of lentil flour. Trials were executed directly at industrial level, and without the need of a successive scale-up. This study is needed in view of selecting the best processing conditions for further food application of the extruded lentil flour, which could be a valuable ingredient either for bakery products or for instant foods, depending on starch gelatinization degree and dough mixing properties. To the authors' best knowledge, this is the first study carried out on the E-C of lentil flour at industrial level.

2. Materials and methods

2.1. Preparation of native and extruded lentil flour

Dehulled lentils (*Lens culinaris* Medik.) having 28.37 g 100 g^{-1} crude proteins, 57.83 g 100 g^{-1} carbohydrates, 10.58 g 100 g^{-1} dietary fiber, 0.96 g 100 g^{-1} total fat, 2.25 g 100 g^{-1} total ashes, all on dry matter (d.m.), were kindly provided by Molino Andriani spa (Gravina in Puglia, Italy). The choice of using dehulled lentils was based on preliminary tests which showed a detrimental effect of dietary fibers contributed by the seed coat on the expansion rate. A single lot of lentils (6000 kg), at 10 g 100 g^{-1} moisture, was preliminary divided into two batches. One batch was milled using an industrial horizontal hammer mill (DNZF-0655 Fine Grinding Mill, Bühler, Uzwil, Switzerland) equipped with a screen having 3 mm holes. The obtained flour was then conditioned to 28 ± 1 g 100 g^{-1} moisture and processed by an industrial twin-screw extruder-cooker (PRIOtwin-BCTF, Bühler, Uzwil, Switzerland) (Fig. 1) according to two different processing conditions, coded E1 (milder) and E2 (more severe), reported in Table 1. These specific E-C conditions were selected after preliminary tests because they allowed to obtain an extruded flour with acceptable to good cold viscosity. The extruder specifications were co-rotating twin screw with 93 mm diameter modular screws, heating system by oil or water/steam, capacity = 500–4500 kg h^{-1}, power = 250 kW. A die with 4 mm diameter round holes was used. The extruded pellet was dried in an industrial drier (Aeroglide, Bühler, Uzwil, Switzerland) set at 110 °C for 14 min, then at 115 °C for 16 min, to reach 12 g 100 g^{-1} moisture. The extruded and dried pellets were then milled using an industrial four-roller mill (MDDP, Bühler, Uzwil, Switzerland) consisting in four break rolls (B_{1A}, B_{1B}, B_2, B_3), and four reduction rolls (C_{1A}, C_{1B}, C_2, C_3), followed by a plansichter (MDPK, Bühler, Uzwil, Switzerland) with 0.2 mm hole

Table 1
Processing conditions (mean ± standard deviation) adopted during the extrusion-cooking of lentil flour, classifiable as milder (E1) and more severe (E2).

Parameter	Extrusion-cooking conditions	
	E1	E2
Feed moisture (g 100 g^{-1})	28.80 ± 0.51	27.10 ± 0.50
Barrel temperature of sectors 2°–3° (°C)	80.00 ± 0.39	100.00 ± 0.44
Barrel temperature of sectors 4°–5° (°C)	90.00 ± 0.32	105.00 ± 0.37
Die head temperature (°C)	100.00 ± 1.01	115.00 ± 1.02
Screw speed (rpm)	220.00 ± 0.95	230.00 ± 0.99
Steam quantity (kg s^{-1})	$69.4 \times 10^{-4} \pm 1.6 \times 10^{-4}$	$99.7 \times 10^{-4} \pm 1.7 \times 10^{-4}$
Die head pressure (Pa)	$665 \times 10^{4} \pm 21 \times 10^{4}$	$759 \times 10^{4} \pm 25 \times 10^{4}$

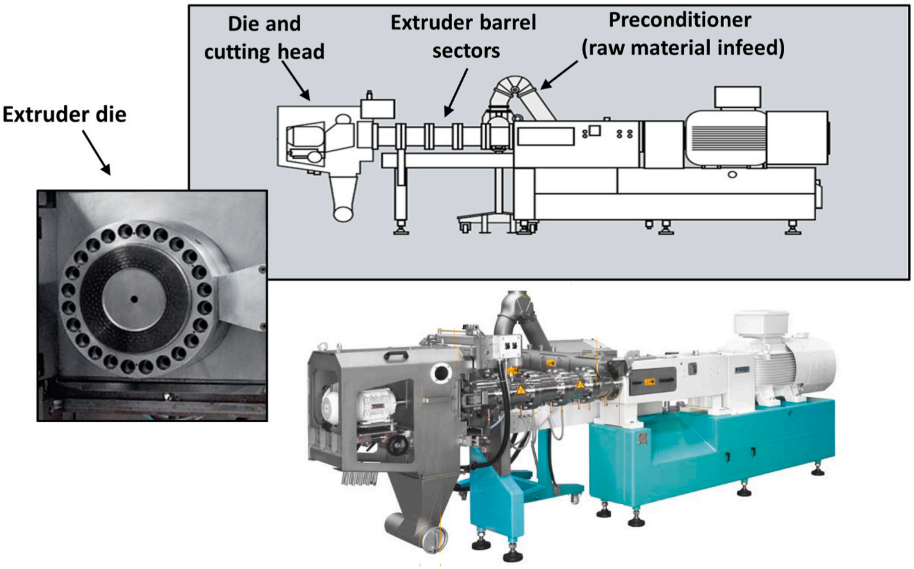

Fig. 1. Scheme of the PRIOtwin-BCTF-93 (Bühler, Uzwil, Switzerland) co-rotating twin screw extruder used in the trials (elaboration from Bühler PRIOtwin leaflet).

sieves, to obtain the extruded flours EF1 and EF2. The same conditions (industrial four-roller mill and plansichter with 0.2 mm holes) were used to grind the remaining batch of dehulled lentils, obtaining the native flour (NF).

2.2. Determination of proximate composition

The content of crude proteins (total nitrogen × 6.25), total ashes, and moisture were determined according to the AOAC methods 979.09, 923.03 and 925.10, respectively (AOAC, 2006). Total, soluble, and insoluble dietary fibers were determined by enzymatic-gravimetric procedure according to the AOAC method 991.43 (AOAC, 2006). The content of total fat was determined by the SER 148 automated extractor (Velp Scientifica, Usmate, Italy) using diethyl ether (Sigma Aldrich, Milan, Italy) as extracting solvent, as described in the AOAC method 945.38F (AOAC, 2006). The carbohydrate content was calculated by difference: 100 − (moisture + crude proteins + total fat + total dietary fibers + total ashes).

2.3. Determination of starch gelatinization profile by viscoamylograph

Starch properties were determined using a viscoamylograph (Brabender Instruments, Duisburg, Germany), according to the protocol set up in lentil flour by Kaur and Sandhu (2010). Flour (10 g, on a 14.0 g 100 g^{-1} moisture basis) was suspended in 100 mL distilled water and subjected to a heating and cooling cycle, starting at 50 °C for 1 min, then reaching 95 °C and holding this temperature for 5 min, and finally cooling to 50 °C and maintaining this temperature for 1 min. The heating/cooling rate was 6 °C/min, with continuous stirring at 250 rpm. The viscosity values at the beginning (initial viscosity, IV), at the peak (peak viscosity, PV), at the end of the holding period at 95 °C (minimum viscosity, MV), and at the end of cooling (cooling maximum viscosity, CMV) were recorded and expressed in arbitrary Brabender units (BU). The differences between PV and MV, and between CMV and MV were defined as “breakdown” and “setback”, respectively. The analysis was conducted in triplicate.

2.4. Determination of the starch gelatinization profile by mixolab

Starch gelatinization profiles were determined also using the Mixolab instrument (Chopin Technologies, Villeneuve-La-Garenne, France). The “Cube protocol” was applied, as this protocol is specific to measure the starch gelatinization degree of extruded products (previously milled) and to highlight differences with native flours (Dubat & Boinot, 2012, p. 79). The Cube protocol focuses only on heating, without including cooling steps. In detail, the Mixolab was programmed to heat at 50 °C, maintain the temperature for 1 min, then heat at 90 °C, maintain this temperature for 10 min, and then stop recording. The heating rate was 8 °C/min, with continuous stirring at 200 rpm. The torque at the beginning of the analysis, i.e., at 50 °C (expressing the maximum consistency, MaxC), the minimum torque produced by dough while being subjected to mechanical and thermal stress (minimum consistency, MinC), and the maximum torque during the heating phase (heating maximum consistency, HMC) were recorded. In addition, the slopes of the descending and ascending curves were calculated, as a measure of protein network weakening rate (α) and gelatinization rate (β), respectively. An amount of 90 g of dough, at 80 g 100 g^{-1} flour hydration (14.0 g 100 g^{-1} moisture basis), was analyzed for each sample. The analysis was conducted in triplicate.

2.5. Dough mixing properties

Dough mixing properties were determined by adopting the “Chopin S” simulator protocol of the Mixolab instrument (Chopin Technologies, Villeneuve-La-Garenne, France), according to the procedure reported by Codină, Mironeasa, Mironeasa, Popa, & Tamba-Berehoiu (2012). The Chopin S protocol did not use the heating section of the Mixolab and simulated the operating conditions of the Farinograph (Brabender Instruments, Duisburg, Germany), i.e.: 80 rpm kneading speed; 30 °C water temperature; 30 °C mixer temperature; 30 min total time of analysis. The tests were performed on 75 g of dough per each sample, at a flour hydration rate able to reach the torque of 1.1 ± 0.05 Nm (Newton meter), corresponding to the consistency of 500 arbitrary Brabender Units, which is the standard dough consistency to perform the analysis by Farinograph (Brabender Instruments, Duisburg, Germany). The following parameters were determined: the percentage of water (water absorption, WA) and time (development time, DT) necessary to produce the maximum torque; the elapsed time at which 1.1 Nm torque was kept (stability time, ST). The analysis was conducted in triplicate.

2.6. Determination of techno-functional parameters of flours

Water absorption index (WAI), water solubility index (WSI), water absorption capacity (WAC), oil absorption capacity (OAC) and bulk density (BD) of flours were determined according to the procedures reported by Du, Jiang, Yu, and Jane (2014). WAI (expressed as g swollen sediment g^{-1} flour) and WSI (expressed as g dissolved solids 100 g^{-1} flour) were assessed after heating a flour suspension in distilled water at 70 °C, while WAC (expressed as g water g^{-1} flour) was assessed at room temperature. OAC (expressed as g oil g^{-1} flour) was determined by mixing 2.5 g of flour with 30 mL of peanut oil in pre-weighed centrifuge tubes, then stirring for 1 min, holding for 30 min, and centrifuging at 3000×*g* for 30 min. The oil layer was then removed, and the tubes were inverted for 25 min to drain the oil from the pellet prior to reweighing. All determinations were performed in triplicate.

2.7. Statistical analysis

All the experimental data were subjected to the one-way ANOVA followed by the Tukey’s HSD test. Significant differences among the values of all parameters were determined at $p < 0.05$ by Minitab 17 Statistical Software (Minitab Inc., State College, PA).

3. Results and discussion

3.1. Proximate composition

Significant differences were observed in the proximate composition of NF, EF1 and EF2 (Table 2), with NF characterized by higher contents of crude proteins, total fat, and dietary fibers. The lipid content is known to decrease during E-C due to the formation of starch-lipid complexes which affect their extractability and quantification (Kamau, Nkhata, &

Table 2

Nutritional compounds (mean ± standard deviation, $n = 3$) of native lentil flour (NF) and extruded lentil flours (EF1 and EF2, obtained according to the two different extrusion-cooking conditions E1, milder, and E2, more severe, as reported in Table 1).

Nutritional compound	Type of lentil flour		
	NF	EF1	EF2
Proteins (g 100 g^{-1} d.m.)	31.69 ± 0.28^{a}	28.17 ± 0.07^{b}	28.04 ± 0.08^{b}
Lipids (g 100 g^{-1} d.m.)	1.42 ± 0.02^{a}	1.04 ± 0.08^{c}	1.18 ± 0.05^{b}
Ashes (g 100 g^{-1} d.m.)	2.48 ± 0.08^{a}	2.45 ± 0.05^{a}	2.41 ± 0.07^{a}
Carbohydrates (g 100 g^{-1} d.m.)	53.81 ± 0.09^{c}	62.64 ± 0.01^{b}	64.12 ± 0.03^{a}
Total dietary fibers (g 100 g^{-1} d.m.)	10.60 ± 0.30^{a}	5.70 ± 0.19^{b}	4.25 ± 0.13^{c}
Insoluble fibers (g 100 g^{-1} d.m.)	8.30 ± 0.20^{a}	4.00 ± 0.02^{b}	2.80 ± 0.13^{c}
Soluble dietary fibers (g 100 g^{-1} d.m.)	2.30 ± 0.09^{a}	1.70 ± 0.05^{b}	1.45 ± 0.04^{c}
Insoluble/soluble fiber ratio	3.61 ± 0.05^{a}	2.35 ± 0.08^{b}	1.93 ± 0.05^{c}

Different letters in line indicate significant differences ($p < 0.05$).

Ayua, 2020). The physic-chemical properties of dietary fiber may also change with E-C, leading to a decrease of total and insoluble dietary fibers resulting from shearing forces and heat transfer (Kamau et al., 2020; Zhong, Fang, Wahlqvist, Hodgson, & Johnson, 2019).

Regarding crude proteins, however, Espinosa-Ramírez et al. (2021), studying the extrusion of whole flours of several cereals, pseudocereals and legumes, including lentils, commented that changes in the protein content reported in some articles are controversial since during the E-C no effluents are produced where fractions could be lost. Also, denaturation, which occurs during E-C, does not affect the quantification of proteins. The difference in protein content observed between NF and the two extruded flours was therefore likely imputable to the double milling process needed to obtain EF1 and EF2, one before and another after the E-C process, both coupled to sieving. The first of these two milling phases, needed to feed the extruder-cooker with smaller and homogeneously sized lentil fragments, was not carried out for NF. This additional step resulted in the reduction of some nutrients of EF1 and EF2 compared with NF, as observed for proteins, not excluding an effect on dietary fiber and lipids.

Comparing EF1 with EF2, instead, no differences were observed in the protein content. Compositional differences, however, were observed in lipids, dietary fiber, and carbohydrates of the extruded flours. As for lipids, the slightly lower content assessed in EF1 could be due to a greater formation of starch-lipid complexes than in EF2. Amylose-lipid complex formation requires starch gelatinization, which makes the amylose available for complexation. Heating expands the diameter of the amylose double helix allowing the lipid to fit, forming electrostatic bonds to get stability. A more severe mechanical stress occurred during the extrusion of EF2 (115 °C, 230 rpm) compared with EF1 (100 °C, 220 rpm), affecting the amylose-lipid complex formation and/or stability (Cervantes-Ramírez et al., 2020).

Similarly, the most intense mechanical stress related to EF2 extrusion also explains the total dietary fiber content of EF2, which was lower than EF1. In addition, a redistribution of the soluble and insoluble fiber fractions due to E-C was observed, which was significantly influenced by the extrusion conditions. EF2, subjected to the most severe E-C conditions, showed the lowest insoluble/soluble fiber ratio due to higher shear forces, in agreement with other studies (Zhong et al., 2019). Morales et al. (2015) observed a decrease in total dietary fibers with a variation of the ratio between the insoluble and soluble fractions after the E-C of fiber-enriched lentil-based snacks at 160 °C and 500 rpm. The soluble fiber of lentil is composed of beta glucans rather than galactomannans (Turfani et al., 2017). Harsher E-C conditions have been reported to cause disintegration of call walls, fiber depolymerization, decrease of beta glucans molecular weight, as well as changes in the distribution of the ratios of β (1 → 3) and (1 → 4) glycosidic bonds of beta glucans in cereal bran (Kaur, Sharma, Ji, Xu, & Agyei, 2020; Zhang, Bai, & Zhang, 2011).

3.2. *Starch pasting profile*

Rheological properties depend on the chemical composition and interaction among food components (Kew, Holmes, Stieger, & Sarkar, 2021) and play a key role in predicting product quality, helping in designing processing conditions to obtain desired food products. Therefore, biochemical modifications of pulse flour polymers during extrusion influence the rheological behavior of extruded flours (Gallego, Arnal, Barat, & Talens, 2021). The starch pasting profile of NF, EF1 and EF2 was determined by viscoamylograph (Table 3) and Mixolab (Table 4). In lentil, a few studies have applied these instruments to the evaluation of the pasting properties of native flours, but no reports are available in the literature on the evaluation of the same raw materials after extrusion which, instead, is essential in view of further using the extruded flour as food ingredient. The viscoamylograph was used for analyzing the pasting properties of native whole seed lentil flour (Ek et al., 2021) and native lentil grits (Ghumman et al., 2016), whereas Marchini et al. (2021) used the Mixolab for studying the rheological and pasting properties of native lentil-wheat flour blends.

Table 3
Starch gelatinization properties (mean ± standard deviation, $n = 3$) of native lentil flour (NF) and extruded lentil flours (EF1 and EF2, obtained according to the two different extrusion-cooking conditions E1, milder, and E2, more severe, as reported in Table 1) determined by viscoamylograph (Brabender Instruments, Duisburg, Germany).

Viscoamylograph parameter	Type of lentil flour		
	NF	EF1	EF2
Initial viscosity (IV, BU)	25.5 ± 1.5^{c}	69.3 ± 4.1^{a}	59.1 ± 3.1^{b}
Peak viscosity (PV, BU)	283.5 ± 8.5^{a}	137.2 ± 7.6^{b}	121.1 ± 3.2^{b}
Minimum viscosity (MV, BU)	275.5 ± 9.5^{a}	121.1 ± 6.1^{b}	108.2 ± 4.1^{b}
Cooling maximum viscosity (CMV, BU)	433.5 ± 8.5^{a}	201.3 ± 6.4^{b}	194.1 ± 9.2^{b}
Breakdown (BU)	13.1 ± 0.1^{a}	16.1 ± 2.6^{a}	13.2 ± 1.1^{a}
Setback (BU)	158.1 ± 7.1^{a}	80.3 ± 0.6^{b}	86.2 ± 5.2^{b}

Different letters in line indicate significant differences ($p < 0.05$); BU = Brabender Units.

Table 4
Starch gelatinization properties (mean ± standard deviation, $n = 3$) of native lentil flour (NF) and extruded lentil flours (EF1 and EF2, obtained according to the two different extrusion-cooking conditions E1, milder, and E2, more severe, as reported in Table 1) determined by Mixolab (Chopin Technologies, Villeneuve-La-Garenne, France).

Mixolab parameter	Type of lentil flour		
	NF	EF1	EF2
Maximum consistency (MaxC, Nm)	n.r.	1.77 ± 0.04^{a}	1.63 ± 0.02^{b}
Protein network weakening (α, Nm min^{-1})	n.r.	−0.11 ± 0.01^{a}	−0.12 ± 0.01^{a}
Minimum consistency (MinC, Nm)	n.r.	1.14 ± 0.02^{a}	1.11 ± 0.01^{a}
Gelatinization rate (β, Nm min^{-1})	0.16 ± 0.01	n.r.	n.r.
Heating maximum consistency (HMC, Nm)	1.49 ± 0.01^{a}	1.42 ± 0.01^{b}	1.30 ± 0.01^{c}

Different letters in line indicate significant differences ($p < 0.05$); n.r. = not recorded. Torque was expressed in Nm (Newton meter), where 1.1 Nm is equivalent to 500 Brabender Units.

The viscoamylograph analysis (Table 3) showed that NF paste was significantly ($p < 0.05$) more viscous than EF1 and EF2 at elevated temperature (PV) and during cooling (MV and CMV), but not at the beginning of the analysis (IV). A similar behavior was observed by other authors who compared native and extruded bean flours (Mitrus et al., 2020). NF, therefore, showed a greater setback and a lower IV than EF1 and EF2, due to the presence of native starch granules, which gelatinized during the analysis. On the contrary, the starch of EF1 and EF2 gelatinized during the E-C process, deconstructing the granules, and increasing their water absorption. In turn, the initial viscosity measured by the viscoamylograph was raised.

The two E-C conditions considered (Table 1), milder (E1) and more severe (E2), both induced starch gelatinization, but at greater extent in EF1, as shown by its higher IV. Furthermore, differences (despite not significant) were found between EF1 and EF2 for all the other viscoamylograph parameters, with EF2 characterized by a lower gel viscosity. The processing conditions adopted to obtain EF1, therefore, could be suitable to prepare “convenience products”, i.e., precooked instant flours dried by manufacturers and reconstituted in water by consumers to give a ready-to-eat viscous paste. These findings were due to the most intense mechanical stress related to higher E-C temperature and screw speed during the extrusion of EF2 (set at 27.1 g 100 g^{-1} feed moisture, 100–105 °C barrel temperature, 115 °C die head temperature, and 230 rpm screw speed) compared with EF1 (set at set at 28.8 g 100 g^{-1} feed moisture, 80–90 °C barrel temperature, 100 °C die head temperature, and 220 rpm screw speed). High screw speed was reported to have a negative effect on gelatinization, lowering the initial viscosity and raising the peak viscosity of extruded flours in a viscoamylograph profile (Mitrus et al., 2020), in agreement with the observed results. High shear causes degradation of starch with crystal melting of amylopectin molecules as well as dextrinization (Mosibo, Ferrentino, Alam, Morozova, & Scampicchio, 2020). On the other hand, higher feed moisture might have also contributed to increase the degree of starch gelatinization in the E1 processing condition. Higher feed moisture was found to limit the mechanical disruption and fragmentation of starch granules because water acts as a plasticizer in the extruder (Natabirwa, Muyonga, Nakimbugwe, & Lungaho, 2018). The detrimental effects on starch related to the greater mechanical stress of the E2 processing condition reflected the different extent of degradation of dietary fiber observed comparing EF1 and EF2.

Both the E-C conditions markedly limited the starch retrogradation, lowering the CMV and setback values, compared with NF. This effect would be appreciated in bread and bakery products, whose shelf-life is affected by starch retrogradation. Therefore, both the extruded lentil flours could be used to reformulate bread or bakery products, also gluten-free, better than NF.

The addition of lentil flour to wheat-based baked goods has been considered by Kohajdová, Karovičová, and Magala (2013) and by Marchini et al. (2021), but in these studies pulse flour was considered in its native form. Marchini et al. (2021) studied the dough rheology of lentil-wheat flours blends and highlighted a significant influence on gelatinization, with a reduced retrogradation compared with wheat flour alone, therefore suggesting the use of lentil flour up to 10% to improve the shelf-life of bakery products. These findings were advanced by our results which highlight that EF1 and EF2 had even a lower tendency to retrograde than NF (lower setback), indicating that the addition of extruded lentil flours to baked goods could result in further improvement of shelf-life.

The pasting properties of NF were like those reported by Santos et al. (2018) in 47 lentil accessions. The high PV of gels from NF was due to the ability of ungelatinized starch to swell during the heating phase. The extremely limited breakdown observed for all the samples, without significant differences among them, yielded a stable paste viscosity and a good shearing resistance in lentil gels. A limited or even absent breakdown was reported also by Ek et al. (2021) in whole seed native flour from three commercial lentil varieties, and by Ghumman et al. (2016) in native lentil grits.

The gelatinization profiles recorded by Mixolab (Table 4) highlight that the consistency of NF at the beginning of the analysis (i.e., at 50 °C) remained low, because the native starch present in NF required temperatures higher than 50 °C to gelatinize. Therefore, MaxC and, so, MinC, were not recordable for NF. On the contrary, EF1 and EF2, which had pregelatinized starch, swelled at 50 °C. A significantly higher MaxC value was observed in EF1 than EF2, in agreement with the trend shown by the viscoamylograph IV value, remarking that EF1 had a higher content of pregelatinized starch than EF2. MaxC is an important index to obtain immediate information on the maximum consistency at low temperature, which can vary among flours extruded in different conditions, as observed. Therefore, in performing the Mixolab analysis, the Cube protocol (Dubat & Boinot, 2012, p. 79) was preferred over the commonly used Chopin + standard protocol. The latter imposes to reach a starting torque of 1.1 Nm, not allowing to evaluate the real value of MaxC.

The protein network weakening rate (α) was not measurable for NF because of the lack of consistency variations after the initial heating to 50 °C. The protein network weakening is due to structural modifications of proteins following the thermal and mechanical stress induced by the instrument during the analysis which, in turn, is related to the content, structure and functionality of proteins in the sample. EF1 and EF2, which had similar protein content, showed similar α index.

Due to the presence of pregelatinized starch, EF1 and EF2 formed gels with a certain elasticity and strength, which resulted in higher values of minimum consistency (MinC) compared with NF. In addition, E-C induced protein denaturation, and exposure of disulfide bond sites, contributing to cross linking in the dough (Mosibo et al., 2020). When the value of MinC is less than 0.4 Nm, indeed, dough quality is considered extremely poor, showing a not workable dough (Hou et al., 2020).

The β index, which describes the rate of gelatinization occurring when the temperature is raised to 90 °C, was measurable only in NF. In fact, native starch, able to gelatinize with heating, was present only in NF. For the same reason, the maximum consistency recorded at the end of the heating phase (HCM) was significantly higher in NF than EF1 and EF2. No further gelatinization (no β recordable) was observed in EF1 and EF2 during the analytical step which involved heating from 50 to 90 °C, again due to the presence of pregelatinized starch in the extruded-cooked flours.

The retrogradation of starch, instead, was not evaluated during the Mixolab analysis, because no cooling steps were programmed, according to the Cube protocol (Dubat & Boinot, 2012, p. 79).

Finally, a comparison of results obtained by viscoamylograph and Mixolab can be done. Considering the heating steps only, the profiles of NF obtained with the two instruments were similar, whereas those of the extruded flours showed a marked difference. The Mixolab profile of EF1 and EF2, in fact, did not show any increase in dough consistency during the heating step from 50 to 90 °C, indicating that starch had already been completely pregelatinized during the E-C process. The increase in consistency, instead, was observed in the viscoamylograph curve. Therefore, the pasting profile obtained through Mixolab made it possible to evaluate, in a much more reliable way than using the viscoamylograph, the degree of starch gelatinization reached during the E-C process. However, the viscoamylograph analysis complemented very well the Mixolab data derived by the application of the Cube protocol, because gave information on starch retrogradation during the cooling step.

3.3. *Dough mixing properties*

Considered that the extruded lentil flours could be used in the preparation of bakery products, it is fundamental to assess also the dough mixing properties. At this purpose, the Mixolab appeared particularly convenient being able to simultaneously analyze the pasting properties of starch and the consistency of the dough during mixing, therefore replacing the separate use of viscoamylograph and Farinograph (Schmiele, Felisberto, Clerici, & Chang, 2017). The Mixolab, in fact, can measure the rheological behavior of the dough subjected to the dual constraint of constant mixing and temperature changes. In the first part of the analysis, at constant temperature, Mixolab supplies information about water absorption, dough development time, and dough stability, similarly to the Farinograph.

NF, EF1 and EF2 significantly differed ($p < 0.05$) in mixing properties, with clearer differences between NF and the two EFs (Table 5). In particular, the E-C markedly improved the water absorption (WA) of lentil flour, with EF1 reaching the value of 94.65 g 100 g^{-1}. The greater ability of the extruded flours to absorb water was due to the presence of pregelatinized starch (Jafari, Koocheki, & Milani, 2017). Interest in WA is due to its ability to predict how the flour will behave during the preparation of bakery products, particularly in terms of baking yield (Ma et al., 2019). DT showed the same trend as WA, because higher WA values extend the duration of time for water to be fully absorbed by the flour. Consequently, longer times were needed to develop the dough (Codină & Mironeasa, 2016).

Dough stability gives information on dough strength. Low values of

Table 5
Dough mixing properties (mean ± standard deviation, $n = 3$) of native lentil flour (NF) and extruded lentil flours (EF1 and EF2, obtained according to the two different extrusion-cooking conditions E1, milder, and E2, more severe, as reported in Table 1).

Determination	Type of lentil flour		
	NF	EF1	EF2
Water absorption (WA, g 100 g^{-1})	41.1 ± 0.1^c	94.7 ± 0.1^a	90.8 ± 0.1^b
Development time (DT, min)	1.1 ± 0.1^c	10.1 ± 0.1^a	8.05 ± 0.7^b
Stability time (ST, min)	1.5 ± 0.1^b	2.4 ± 0.1^a	2.1 ± 0.5^{ab}

Different letters in line indicate significant differences ($p < 0.05$).

stability time (ST) indicate that dough is less tolerant to mixing and heating (Hou et al., 2020). The stability of dough obtained from NF was quite low, due to the absence of gluten. An improvement in stability would be needed in the preparation of bakery products (Naqash et al., 2017). Addition of lentil flour to wheat bread has been reported to worsen dough handling and baking properties (Marchini et al., 2021). Kohajdová et al. (2013), studying the effect of lentil flour addition on the mixing properties of wheat dough, observed an increase of WA and DT, whereas ST decreased.

EF1 and EF2, however, showed a longer dough stability than NF due to the presence of pregelatinized starch, which performs a "binding" function being capable to develop a viscous phase in the dough without the need for heating (Wang, Warkentin, Vandenberg, & Bing, 2014). In addition, also the denatured protein fraction might contribute to reticulation by covalent and non-covalent bonds involving the newly exposed residues (Mosibo et al., 2020). Despite not significantly different, EF2 had a slightly lower stability than EF1, a cause being the high mechanical stress related to EF2 extrusion conditions. Data of dough mixing properties agreed with the Mixolab MinC values.

The potential use of EF1 for gluten-free baked goods seems therefore very promising, which is particularly interesting because this type of ingredient would not be classified as additive and would meet the clean label requirements of the modern food industry (Espinosa-Ramírez et al., 2021).

3.4. Techno-functional parameters

To set up the best food application of extruded flours, also their techno-functional properties (i.e., water absorption and solubility, oil absorption, and bulk density) should be evaluated. These parameters also provide information on the physic-chemical changes affecting the constituting macromolecules because of E-C conditions.

Table 6
Techno-functional parameters (mean ± standard deviation, $n = 3$) of native lentil flour (NF) and extruded lentil flours (EF1 and EF2, obtained according to the two different extrusion-cooking conditions E1, milder, and E2, more severe, as reported in Table 1).

Determination	Type of lentil flour		
	NF	EF1	EF2
Water absorption capacity (WAC, g water g^{-1} flour)	1.09 ± 0.05^b	2.01 ± 0.07^a	1.95 ± 0.01^a
Water solubility index (WSI, g dissolved solids 100 g^{-1} flour)	20.17 ± 0.03^c	23.87 ± 0.04^b	24.80 ± 0.58^a
Water absorption index (WAI, g swollen sediment g^{-1} flour)	3.51 ± 0.02^c	4.32 ± 0.04^a	4.10 ± 0.10^b
Oil absorption capacity (OAC, g oil g^{-1} flour)	0.87 ± 0.02^c	0.92 ± 0.01^b	1.05 ± 0.01^a
Bulk density (BD, g mL^{-1})	0.83 ± 0.01^a	0.75 ± 0.01^b	0.72 ± 0.01^c

Different small letters in line indicate significant differences ($p < 0.05$).

Significant differences ($p < 0.05$) were found among flours for all the techno-functional parameters considered (Table 6). EF1 and EF2 showed higher values of WAC, WSI, WAI and OAC than NF, and a lower value of BD.

Compared to NF, a two-fold increase of WAC was observed in EF1 and EF2. WAC depicts the amount of water held by the sample at room temperature. In the extruded flours, WAC was triggered by the gelatinization and melting of molecules during E-C, as well as by unwrapping of biopolymers, such as proteins, with exposure of more hydrophilic groups to an interaction with water (Mosibo et al., 2020). The hydration capacity of NF, instead, was mostly imputable to its higher content of dietary fibers and to the presence of hydrophilic groups in native pulse proteins. The WAC values reflected those of WA, determined by Mixolab.

WAI and WSI were determined after heat treatment of an aqueous suspension of flour. WAI measures the weight of hydrated polymers, whereas WSI estimates the number of soluble molecules derived from the degradation of starch, proteins, and dietary fiber (Lazou & Krokida, 2010). EF1 and EF2 showed higher WAI and WSI than NF, in agreement with current literature on the effects of E-C on pulse flours (Pasqualone et al., 2020).

WAI depicts the amount of water held by the extrudates. It is triggered by the gelatinization and melting of molecules (Mosibo et al., 2020). The observed values of WAI (4.32 ± 0.04 g g^{-1} and 4.10 ± 0.10 g g^{-1} for EF1 and EF2, respectively) were like those assessed by Ek et al. (2021) in whole seed extruded lentil flour. An increase of WAI was observed as the extrusion temperature decreased from 115 to 100 °C and screw speed decreased from 230 to 220 rpm, in agreement with the findings of Ghumman et al. (2016). Higher screw speed leads to higher shear, resulting in an extensive molecular breakdown which, in turn, causes higher WSI and lower WAI in the extruded flours. WAI, indeed, has been reported to be negatively correlated with the specific mechanical energy of the extrusion process (Ek et al., 2021).

Regarding the effect of temperature, however, Ek et al. (2021) found that WAI increased as temperature increased. In contrast, Ghumman et al. (2016) observed the opposite behavior, consistent with the findings of our experiments. This difference between studies may be due to a different degree of starch degradation. At higher temperatures, the starch granules are disrupted and tend to bind more water, however this phenomenon occurs up to a limit, at which starch degradation prevails (Ghumman et al., 2016).

WSI increased at higher extrusion temperature (115 °C) and screw speed (230 rpm), i.e., in E2, because the related greater mechanical stress degraded macromolecules to a greater extent than at 100 °C and 220 rpm (E1), in agreement with earlier studies (Pasqualone et al., 2020). In addition, higher moisture content (as in E1) is known to reduce starch depolymerization during E-C (Guillermic et al., 2021).

The OAC of extruded flours was higher than NF, due to a higher level of starch degradation in the extrudates due to the high input of thermal energy. Similar findings were reported by de la Rosa-Millán, Heredia-Olea, Perez-Carrillo, Guajardo-Flores, and Serna-Saldívar (2019) on extruded black beans, due to the starch depolymerization and protein denaturation caused by the intensive heat treatment during extrusion.

OAC data for EF1 and EF2 were in the range of values (0.77–1.07 g g^{-1}) reported by Ghumman et al. (2016), who studied the effect of feed moisture and extrusion temperature on lentil techno-functional properties. These authors observed an OAC increase at higher temperature (from 100 to 150 °C) but did not find a clear effect of feed moisture because the OAC increased raising moisture from 15 to 20 g 100 g^{-1} but decreased when moisture increased to 25 g 100 g^{-1}, at fixed screw speed (300 rpm). In our trials we observed a significant increase in OAC raising the temperature from 100 to 115 °C, decreasing the feed moisture from 28.8 to 27.1 g 100 g^{-1}, and increasing screw speed from 220 to 230 rpm. Similarly, Lazou and Krokida (2010) observed an increase of the OAC of corn–lentil extrudates when E-C temperature increased, and feed moisture decreased.

The changes in OAC were mostly due to protein modifications during E-C (denaturation and successive aggregation of denatured molecules) influencing their conformational characteristics. Self-assembly of proteins is controlled by a delicate interplay between hydrophobic and hydrophilic interactions which makes them able to interact with water and oily phases of foods. The OAC is enhanced by an increase in the hydrophobic character of proteins, i.e., by the availability of non-polar amino acids and their exposure on the surface of proteins to a greater extent (Mosibo et al., 2020). Higher OAC values, such as in EF2, make the extruded flour more able to maintain food flavor and improve the mouth feel and palatability, which is important for example in pastries and meat analogues. As expected, the trend for OAC was opposite to that observed for WAI.

The main purpose of E-C is direct expansion, therefore the process positively influenced BD, making both EF1 and EF2 less dense than NF. A low BD value is desirable, corresponding to extrudates having a well expanded and porous structure. Lentils have high protein and fiber content, know to hinder expansion, however lentil puffed snacks have been recently developed by Luo et al. (2020) and Guillermic et al. (2021). EF2 showed a significantly lower BD value than EF1, indicating that expansion was favored by higher temperature, higher screw speed, and lower feed moisture, in agreement with other authors (Ghumman et al., 2016; Luo et al., 2020; Rathod & Annapure, 2016).

4. Conclusions

The results of this study, carried out directly at industrial level and immediately applicable without the need of a successive scale-up, evidenced significant differences between the two extrusion conditions considered, with the milder one (namely E1, set at 28.8 g 100 g^{-1} feed moisture, 80–90 °C barrel temperature, 100 °C die head temperature, and 220 rpm screw speed) more effective in increasing flour water absorption and initial viscosity of paste than a more severe extrusion (E2, set at 27.1 g 100 g^{-1} feed moisture, 100–105 °C barrel temperature, 115 °C die head temperature, and 230 rpm screw speed). The oil absorption, on the contrary, increased with more severe conditions, whereas starch retrogradation decreased similarly with both E-C conditions, compared to starting native lentil flour.

Therefore, considering that both the extruded flours showed a reduced tendency to retrograde, the two processing conditions evaluated were both able to produce a lentil-based ingredient suitable for the formulation of baked goods, also gluten-free, less prone to staling. The E2 processing condition, instead, should be adopted when it is necessary to enhance the compatibility with the lipid phase of foods, for example in the production of meat analogues. The E1 processing condition, on the other hand, should be preferred to produce instant flours and, in general, convenience foods that are easy to prepare adding water, without cooking, to be consumed as a viscous paste.

Hence, by appropriately modulating the E-C processing conditions, the food industry could use lentil flour to produce new ingredients with good potential for developing various products. The availability of lentil-based ingredients with the desired characteristics could increase the consumption of this nutritionally valuable crop, with beneficial effects for both producers and consumers.

Declaration of competing interest

The authors declare that they have no conflict of interest.

CRediT authorship contribution statement

Antonella Pasqualone: Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition, Supervision. **Michela Costantini:** Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Rossella Labarbuta:** Data curation, Formal analysis, Writing – review & editing. **Carmine Summo:** Writing – review & editing, Formal analysis, Funding acquisition.

Acknowledgements

The authors are grateful to: Dr. Michele Andriani for kindly guesting the experimental trials at Andriani spa, Gravina in Puglia, Bari, Italy; Dr. Luigi Manfredi for providing the flours; Mr. Roberto Corradino for skillful technical aid; Prof. Tera Fazzino, University of Kansas (USA), for linguistic revision and helpful suggestions.

This research was funded by 1) Agropolis Fondation, Fondazione Cariplo, and Daniel & Nina Carasso Foundation through the “Investissements d’avenir” program with reference number ANR-10-LABX-0001-01, under the “Thought for Food” Initiative (project “LEGERETE”); 2) the Italian Ministry of Education, University and Research (MIUR), program PRIN 2017 (grant number 2017SFTX3Y) “The Neapolitan pizza: processing, distribution, innovation and environmental aspects”.

References

AOAC International. (2006). *Official methods of analysis* (17th ed.). Gaithersburg, MD: Association of Official Analytical Chemists International.

Cervantes-Ramírez, J. E., Cabrera-Ramirez, A. H., Morales-Sánchez, E., Rodriguez-García, M. E., de la Luz Reyes-Vega, M., Ramírez-Jiménez, A. K., et al. (2020). Amylose-lipid complex formation from extruded maize starch mixed with fatty acids. *Carbohydrate Polymers, 246*, 116555.

Ciudad-Mulero, M., Fernández-Ruiz, V., Cuadrado, C., Arribas, C., Pedrosa, M. M., Berrios, J. D. J., et al. (2020). Novel gluten-free formulations from lentil flours and nutritional yeast: Evaluation of extrusion effect on phytochemicals and non-nutritional factors. *Food Chemistry, 315*, 126175.

Codină, G. G., & Mironeasa, S. (2016). Use of response surface methodology to investigate the effects of brown and golden flaxseed on wheat flour dough microstructure and rheological properties. *Journal of Food Science & Technology, 53*, 4149–4158.

Codină, G. G., Mironeasa, S., Mironeasa, C., Popa, C. N., & Tamba-Berehoiu, R. (2012). Wheat flour dough Alveograph characteristics predicted by Mixolab regression models. *Journal of the Science of Food and Agriculture, 92*, 638–644.

De Angelis, D., Pasqualone, A., Costantini, M., Ricciardi, L., Lotti, C., Pavan, S., et al. (2020). Data on the proximate composition, bioactive compounds, physicochemical and functional properties of a collection of faba beans (Vicia faba L.) and lentils (Lens culinaris Medik.). *Data in Brief, 34*, 106660.

De Ron, A. M. (2015). *Grain legumes* (Vol. 10, p. 438). Berlin, Germany: Springer.

Dubat, A., & Boinot, N. (2012). *Mixolab applications handbook. Rheological and enzymes analyses. Villeneuve la Garenne*. France: Chopin Technology.

Du, S. K., Jiang, H., Yu, X., & Jane, J. L. (2014). Physicochemical and functional properties of whole legume flour. *LWT-Food Science and Technology, 55*, 308–313.

Ek, P., Gu, B. J., & Ganjyal, G. M. (2021). Whole seed lentil flours from different varieties (Brewer, Crimson, and Richlea) demonstrated significant variations in their expansion characteristics during extrusion. *Journal of Food Science, 86*, 942–951.

Espinosa-Ramírez, J., Rodríguez, A., De la Rosa-Millán, J., Heredia-Olea, E., Pérez-Carrillo, E., & Serna-Saldívar, S. O. (2021). Shear-induced enhancement of technofunctional properties of whole grain flours through extrusion. *Food Hydrocolloids, 111*, 106400.

Food and Agriculture Organization of the United Nations (FAO). (2018). Data of crops production. http://www.fao.org/faostat/en/#data/QC. (Accessed 26 August 2020).

Gallego, M., Arnal, M., Barat, J. M., & Talens, P. (2021). Effect of cooking on protein digestion and antioxidant activity of different legume pastes. *Foods, 10*, 47.

Ganjyal, G. M. (2020). *Extrusion cooking: Cereal grains processing* (2nd ed.). Amsterdam, Nederland: Elsevier.

Ghumman, A., Kaur, A., Singh, N., & Singh, B. (2016). Effect of feed moisture and extrusion temperature on protein digestibility and extrusion behaviour of lentil and horsegram. *LWT-Food Science and Technology, 70*, 349–357.

Guillermic, R. M., Aksoy, E. C., Aritan, S., Erkinbaev, C., Paliwal, J., & Koksel, F. (2021). X-ray microtomography imaging of red lentil puffed snacks: Processing conditions, microstructure and texture. *Food Research International, 140*, 109996.

Hou, D., Duan, W., Xue, Y., Yousaf, L., Hu, J., & Shen, Q. (2020). Effects of superfine grinding and extrusion on dough mixing properties and noodle quality of black soybean flour. *Journal of Food Measurement and Characterization, 14*, 125–134.

Jafari, M., Koocheki, A., & Milani, E. (2017). Effect of extrusion cooking on chemical structure, morphology, crystallinity and thermal properties of sorghum flour extrudates. *Journal of Cereal Science, 75*, 324–331.

Kamau, E. H., Nkhata, S. G., & Ayua, E. O. (2020). Extrusion and nixtamalization conditions influence the magnitude of change in the nutrients and bioactive components of cereals and legumes. *Food Sciences and Nutrition, 8*, 1753–1765.

Kaur, M., & Sandhu, K. S. (2010). Functional, thermal, and pasting characteristics of flours from different lentil (Lens culinaris) cultivars. *Journal of Food Science & Technology, 47*, 273–278.

Kaur, R., Sharma, M., Ji, D., Xu, M., & Agyei, D. (2020). Structural features, modification, and functionalities of beta-glucan. *Fibers, 8*, 1. https://doi.org/10.3390/fib8010001

Kew, B., Holmes, M., Stieger, M., & Sarkar, A. (2021). Oral tribology, adsorption, and rheology of alternative food proteins. *Food Hydrocolloids*, 106636. https://doi.org/10.1016/j.foodhyd.2021.106636

Kohajdová, Z., Karovičová, J., & Magala, M. (2013). Effect of lentil and bean flours on rheological and baking properties of wheat dough. *Chemical Papers, 67*, 398–407.

Lazou, A., & Krokida, M. (2010). Functional properties of corn and corn–lentil extrudates. *Food Research International, 43*, 609–616.

Luo, S., Chan, E., Masatcioglu, M. T., Erkinbaev, C., Paliwal, J., & Koksel, F. (2020). Effects of extrusion conditions and nitrogen injection on physical, mechanical, and microstructural properties of red lentil puffed snacks. *Food and Bioproducts Processing, 121*, 143–153.

Ma, J., Kaori, F., Ma, L., Gao, M., Dong, C., Wang, J., et al. (2019). The effects of extruded black rice flour on rheological and structural properties of wheat-based dough and bread quality. *International Journal of Food Science and Technology, 54*, 1729–1740.

Marchini, M., Carini, E., Cataldi, N., Boukid, F., Blandino, M., Ganino, T., et al. (2021). The use of red lentil flour in bakery products: How do particle size and substitution level affect rheological properties of wheat bread dough? *LWT-Food Science and Technology, 136*, 110299.

Mitrus, M., Wójtowicz, A., Kocira, S., Kasprzycka, A., Szparaga, A., Oniszczuk, T., … Matwijczuk, A. (2020). Effect of extrusion-cooking conditions on the pasting properties of extruded white and red bean seeds. *International Agrophysics, 1*, 25–32.

Morales, P., Cebadera-Miranda, L., Cámara, R. M., Reis, F. S., Barros, L., Berrios, J. D. J., … Cámara, M. (2015). Lentil flour formulations to develop new snack-type products by extrusion processing: Phytochemicals and antioxidant capacity. *Journal of Functional Foods, 19*, 537–544.

Mosibo, O. K., Ferrentino, G., Alam, M. R., Morozova, K., & Scampicchio, M. (2020). Extrusion cooking of protein-based products: Potentials and challenges. *Critical Reviews in Food Science and Nutrition*, 1–22. https://doi.org/10.1080/10408398.2020.1854674

Naqash, F., Gani, A., Gani, A., & Masoodi, F. A. (2017). Gluten-free baking: Combating the challenges-A review. *Trends in Food Science & Technology, 66*, 98–107.

Natabirwa, H., Muyonga, J. H., Nakimbugwe, D., & Lungaho, M. (2018). Physico-chemical properties and extrusion behaviour of selected common bean varieties. *Journal of the Science of Food and Agriculture, 98*, 1492–1501.

Nedumaran, S., Abinaya, P., Jyosthnaa, P., Shraavya, B., Rao, P., & Bantilan, C. (2015). *Grain legumes production, consumption and trade trends in developing countries; working paper series No. 60. ICRISAT research program, markets, institutions and policies*. Telangana, India: International Crops Research Institute for the Semi-Arid Tropics – ICRISAT.

Pasqualone, A., Costantini, M., Coldea, T. E., & Summo, C. (2020). Use of legumes in extrusion cooking: A review. *Foods, 9*, 958.

Rathod, R. P., & Annapure, U. S. (2016). Effect of extrusion process on antinutritional factors and protein and starch digestibility of lentil splits. *LWT-Food Science and Technology, 66*, 114–123.

de la Rosa-Millán, J., Heredia-Olea, E., Perez-Carrillo, E., Guajardo-Flores, D., & Serna-Saldívar, S. R. O. (2019). Effect of decortication, germination and extrusion on physicochemical and in vitro protein and starch digestion characteristics of black beans (Phaseolus vulgaris L.). *LWT-Food Science and Technology, 102*, 330–337.

Santos, C. S., Carbas, B., Castanho, A., Bronze, M. R., Serrano, C., Vasconcelos, M. W., … Brites, C. (2018). Relationship between seed traits and pasting and cooking behaviour in a pulse germplasm collection. *Crop & Pasture Science, 69*, 892–903.

Schmiele, M., Felisberto, M. H. F., Clerici, M. T. P. S., & Chang, Y. K. (2017). Mixolab™ for rheological evaluation of wheat flour partially replaced by soy protein hydrolysate and fructo-oligosaccharides for bread production. *LWT-Food Science and Technology, 76*, 259–269.

Turfani, V., Narducci, V., Durazzo, A., Galli, V., & Carcea, M. (2017). Technological, nutritional and functional properties of wheat bread enriched with lentil or carob flours. *LWT-Food Science and Technology, 78*, 361–366.

Wang, N., Warkentin, T. D., Vandenberg, B., & Bing, D. J. (2014). Physicochemical properties of starches from various pea and lentil varieties, and characteristics of their noodles prepared by high temperature extrusion. *Food Research International, 55*, 119–127.

Zhang, M., Bai, X., & Zhang, Z. (2011). Extrusion process improves the functionality of soluble dietary fiber in oat bran. *Journal of Cereal Science, 54*, 98–103.

Zhong, L., Fang, Z., Wahlqvist, M. L., Hodgson, J. M., & Johnson, S. K. (2019). Extrusion cooking increases soluble dietary fibre of lupin seed coat. *LWT-Food Science and Technology, 99*, 547–554.