Processing a 100% legume pasta in a classical extruder without agglomeration during mixing

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Abstract: Pasta made exclusively from legume has high nutritional potential (rich in protein and gluten free). However, it is difficult to produce 100% legume dough suitable for the extrusion step in pasta production that comprises hydration, mixing, and extrusion. This paper addresses the biochemical phenomena at the origin of the agglomeration of dough particles frequently reported in the literature, which results in very sticky dough that cannot be extruded. We tested changes in mixing conditions including mixing temperature, addition of antioxidants, and flour pretreatment. Our results suggest that enzymatic reactions, notably lipoxygenase related redox activity, are responsible for this impairment of dough mixing and extrusion. Some of the process conditions studied can be applied at industrial scale and will help produce a legume food with nutritional and culinary qualities, beneficial for people with celiac disease, or gluten intolerance, as well as the general population.

Keywords: antioxidant, extrusion, faba, lentil, red-ox enzymes, wheat

Practical Application: In the context of a sustainable and healthy food transition, the food industry is developing legume-based food of high nutritional quality that is widely consumed, like pasta. However, using legumes often leads to techno-logical problems during the mixing and extrusion of pasta. This article demonstrates they are linked to enzymatic oxidative phenomena and provides an easy solution to reduce the problems without drastically changing pasta processing. Applied at industrial scale, it will allow the production of naturally gluten-free pasta rich in protein (two to three times the protein content of wheat pasta), of good nutritional quality.

1. INTRODUCTION

Regular wheat pasta, traditionally made of durum wheat (*Triticum durum*) semolina, is one of the simplest wheat products in terms of ingredients (Marti & Pagani, 2013). It is tradition-ally obtained after three main processing steps: water hydration of semolina and mixing to form crumbly dough, extrusion, and finally drying. Dried pasta is mainly composed of carbohydrates (70%) and proteins (12%), whereas lipids, fibers and ash are mi-nor fractions. Recent dietary trends focusing on highly nutritious foods, rich in plant protein and fibers, open new opportunities for innovative pasta made partly or entirely of legume flours. Ac-cording to most authors, adding up to 30% legume flour to wheat semolina does not require any major changes to pasta production processes (Rayas-Duarte, Mock, & Satterlee, 1996; Torres, Frias, Granito, Guerra, & Vidal-Valverde, 2007; Zhao, Manthey, Chang, Hou, & Yuan, 2005). However, incorporating 35% legume flour re-quires a minor change in the process, mainly consisting in reducing the required amount of hydration water (from 47% to 44% on a dry basis) and increasing the mixing speed from 60 to 120 rpm (Petitot, Boyer, Minier, & Micard, 2010). Indeed, when more than 35% of wheat flour is replaced by legume flour, heterogeneous sticky and gummy large dough lumps are formed rendering the extrusion step difficult or even impossible (Jayasena & Nasar-Abbas, 2012; Petitot et al., 2010; Wood, 2009). In this study, we investigated the effect of different pasta production parameters made from 100%

legume flours, using the same standard pasta processing steps (i.e., hydration, mixing, and extrusion) and a standard single screw pasta press, at laboratory and pilot scales. We focused on the hydration-mixing step in which technical problems have frequently been en-countered, and explored the effect of different conditions includ-ing the amount of water hydration, the mixing temperature, and the addition of antioxidant in relation to the extrusion pressure indicating the ability of the dough to be extruded. Our results en-abled us to identify the origin of the lump formation according to the specific biochemical properties of the legume flour. Optimal conditions for producing 100% legume pasta inspired by these re-sults and previously patented (Laleg, Cassan, Abecassis, & Micard, 2016a) are described here. The culinary and sensory properties of the 100% legume free pasta obtained are already detailed and pub-lished in Laleg, Cassan, Barron, Prabhasankar, and Micard (2016b) and Laleg, Barron, Cordelle, Schlich, Walrand & Micard, 2017.

2. MATERIAL AND METHODS

Durum wheat semolina was supplied by La Semoulerie de Bellevue (Marseille), dehusked faba bean (*Vicia faba*), and organic green lentil (*Urvum lens L.*) flours were supplied by GEMEF (Aix-en-Provence, France) and Celnat Industries (Saint-Germain-Laprade, France), respectively. Both the flours originated from non-genetically-modified grains and were not subjected to any pre-treatment. Flours and semolina were conserved at 4 °C.

2.1 Physicochemical and biochemical characterization of raw materials

The moisture content of raw material was determined in trip-licate using a dry air oven heated to 105 °C for 3 hr. Particle size distribution of raw materials was analyzed in triplicate on a Coul-ter LS 230 laser diffraction particle size analyzer (Beckman Coulter Inc., Fullerton, CA, USA).

Total starch content was determined in triplicate with an enzymatic assay kit (Megazyme, Co. Wicklow, Ireland; AACC method 76-13.01). Total protein content was determined in triplicate using the Kjeldahl procedure (NF V 03–050, 1970) with a conversion factor of 6.25. Lipid content was determined in duplicate according to the French NF ISO 6492 and NF-EN-ISO 12966-2 norms by Inovalys (Nantes, France), respectively with a standard deviation of the method lower than 5%. Total, soluble and insoluble fibers were determined in duplicate by ISHA (Longjumeau, France) according to the JORF (1986) method (with a standard deviation lower than 5%).

Lipoxygenase activity (Lox) of flours was determined in triplicate as described by Szymanowska (2009). One gram of legume flour was suspended in 50 mL M/15 phosphate buffer pH 5.5 and lipoxygenase was extracted on a magnetic stirrer for 3 hr at 4 °C. The homogenate was filtered through Whatman paper and centrifuged at 1,000 g for 15 min at 4 °C. The supernatant was used for lipoxygenase determination.

Lipoxygenase activity was determined spectrophotometrically at room temperature by measuring the increase in absorbance at 234 nm over a period of 5 min. The reaction mixture contained 2.97 mL phosphate buffer, 20 μL substrate solution (linoleic acid 2.5 mM) and 10 μL enzyme solution. The blank sample contained 2.98 mL phosphate buffer (pH 5.5) and 20 μL substrate solution. One unit of LOX activity was defined as an increase absorbance of 0.001 per minute at 234 nm. The standard deviation of the method used is lower than 5%.

The total antioxidant capacity of the lentil flours and the 41% hydrated lentil dough was determined in triplicate as Trolox equivalent antioxidant capacity (TEAC) according to Serpen et al. (Serpen, Gökmen, Pellegrini, & Fogliano, 2008).

2.2 Pasta production

All the pasta, including optimization of the mixing and extrusion assays described hereafter, were produced using a lab-scale single-screw pasta extruder (Sercom, Montpellier, France). On this extruder, 500 grams of each raw material (faba bean flour, lentil flour, and durum wheat semolina) were hydrated with demineralized water (the amount of water always took into account the water initial content of raw matters) to obtain a sandy dough and then mixed for 20 min at 60 rpm for Durum wheat semolina and at 120 rpm for legume flours (Petitot et al., 2010). The Durum wheat semolina was mixed at room temperature whereas legume flours were mixed either at room temperature or at 12 °C to 14 °C (see section 2.2.2). The doughs were extruded at 20 rpm and 40 °C. The extrusion pressure at the head of the extrusion press was recorded using a pressure indicator (Gentran Inc., Fremont, CA, USA).

In addition, the production of pasta made from Faba bean and lentil flours were scaled up using a single screw Bassano extruder (Lyon, France): 5 kg of faba bean and lentil flours were hydrated at 43% and 41%, with demineralized water, respectively and then mixed at 12 °C for 20 min at 120 rpm. The doughs were extruded at 31 rpm and 40 °C.

Both lab and pilot scale extruded spaghetti were then dried in a pilot scale drier (AFREM, Lyon, France) at 55 °C, to reach 12% moisture (i.e., relative humidity in the drier decreasing from 92% to 72%). All pasta were produced in duplicate and then mixed into one single batch.

2.2.1 Dough hydration. The minimum water required for dough formation was first evaluated according to the method of Landillon et al. (Landillon, Cassan, Morel, & Cuq, 2008) established
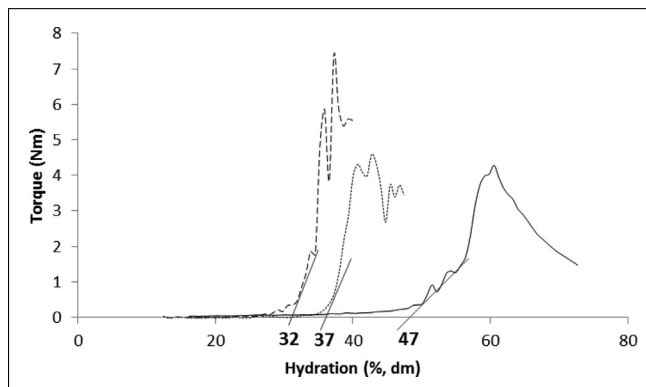

Figure 1–Torque registration as a function of water addition (1 mL/min): Determination of the minimum water content for dough formation (MinW) of durum wheat, faba bean, and lentil doughs on a farinograph-plasticorder (mixing speed 63 rpm). - - -, lentil flour; · · ·, faba bean flour; —, wheat semolina.

for wheat powders. Each raw material (50 g) was continuously hydrated at 25 °C, at a constant rate (1 mL/min) and concomitantly mixed at a constant speed (63 rpm) using a Farinograph small volume mixing bowl (Brabender, OGH, Duisburg, Germany) connected to a Plasticorder PL200 drive system (Brabender, OGH) equipped with a torquemeter. Mixing torque was plotted against water content. The minimum water content for dough formation (MinW, % dry base) was recorded (Figure 1). It corresponds to the critical water content at which a rapid increase in torque is measured.

Using the Landillon et al. (2008) method, the MinW for our wheat semolina, faba bean flour, and lentil flour was 47%, 37%, and 32% (db), respectively.

A hydration level equivalent to its MinW was then successfully used to produce wheat pasta at lab scale and in continuous pilot extruders. However, for legume doughs and according to preliminary tests, the MinW determined by the Landillon's et al. (2008) method resulted in a dry legume dough that was unsuitable for pasta production. So, it was used as a minimum value to start the exploration of higher hydration rates for both legume flours. Water contents ranging between 37% and 44% for faba bean, and from 32% to 41% for lentil were tested. We present results from 37% to 41% and 37% to 44% for lentil and faba bean flours, respectively.

2.2.2 Dough mixing time and temperature. The standard and continuous extrusion step generally starts from 20 min of mixing and is complete after 40 min of mixing (Petitot et al., 2010; Laleg et al., 2016b). In our mixing studies, we therefore continued the mixing step for up to 40 min. Mixing took place at room temperature (25 °C) for all the hydration levels tested.

In addition, on one dough hydration level for each legume flour giving huge agglomeration phenomena with similar particle size distribution (Table 2) during the mixing step (i.e., 43% and 41% for faba bean and lentil flours, respectively), the following changes in process parameters were tested independently in order to further explain the agglomeration phenomena.

Temperature: We tested the use of low temperatures during mixing by refrigerating the mixing tank at 12 °C to 14 °C using a water bath. We also thermally pretreated lentil and faba legume flours by subjecting them to heat treatment (90 °C) for 60 min prior to manufacturing pasta at room temperature using a pilot–scale drier (AFREM). The relative humidity of the dryer was set at less than 16% to avoid modifying starch properties through gelatinization phenomenon.

Table 1–Composition and particle size distribution of raw materials.

Raw material	Moisture (%)	Particle size distribution[a] (µm) D10	D50	D90	Proteins	Fibers[b] (%, dry base) total	soluble	Lipids[b]	Starch
Wheat semolina	14.6 ± 0.0	81 ± 1	273 ± 1	519 ± 10	13.1 ± 0.0	2.4	0.7	1.7	77.8 ± 0.6
Faba bean flour	10.8 ± 0.1	6 ± 0	27 ± 0	100 ± 2	24.0 ± 0.1	11.7	1.2	1.4	57.6 ± 0.3
Lentil flour	12.6 ± 0.0	8 ± 0	25 ± 0	137± 3	28.1 ± 0.1	16.5	1.9	1.7	48.6 ± 0.3

[a]D10, D50, D90 represent the value of particle diameter (in µm) for which 10%, 50% or 90% of the sample's mass has smaller diameter, respectively.
[b]The standard deviation of the used methods is lower than 5%.

Table 2–Particle size distribution of doughs, agglomeration time, and pressure registered during the mixing and extrusion steps, respectively using a lab scale extruder.

Raw material	Water hydration (%, dry base)	Mixing time (min)	Particle size distribution (mm)[a] D10	D50	D90	Agglomeration time (min)[b, c]	Extrusion pressure stabilization (x 10^{7} Pa)
Wheat Semolina	47	20	0	0.5	2.2	> 40	1.172
Faba bean flour	37	20	0.0	0.3	1.1	> 40	>1.724
	38	20	0.1	0.9	1.5	> 40	>1.724
	39	20	0.1	1.0	1.5	> 40	>1.724
	40	20	0.2	0.9	1.6	> 40	>1.724
		40	0.0	0.6	2.5	> 40	>1.724
	41	20	0.0	0.6	1.6	> 40	>1.724
		40	0.0	0.8	3.6	> 40	>1.724
	42	20	0.0	0.7	3.5	> 40	1.172
		40	0.5	2.8	5.9	> 40	1.172
	43	20	0.0	0.8	4.0	30	–
		40	3.3	6.5	9.4	30	–
	44	20	0.1	1.0	4.0	25	–
		40	3.9	7.5	9.5	25	–
Lentil flour	37	20	0	0.5	1.7	> 40	>1.724
		40	0	0.7	2.6	> 40	> 1.724
	38	20	0	0.5	1.5	> 40	>1.724
		40	0	0.5	1.6	> 40	>1.724
	39	20	1.0	7.1	9.5	14	–
		40	1.5	4.4	8.8	14	–
	40	20	0.9	4.5	8.6	10	–
		40	0.6	3.8	6.6	10	–
	41	20	4.2	6.4	9.3	7	–

– no extrudable.
[a]D10, D50, D90 represent the value of particle diameter (in mm) for which 10%, 50%, or 90% of the sample's mass has smaller diameter, respectively.
[b]>40: implies particles did not agglomerate during the 40 min mixing period.
[c]precision ± 30 s.
Grey area shows the conditions that make extrusion of the dough possible.

Use of additives during mixing: Three antioxidants (Ascorbic Acid [AA], Trolox [6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid] and BHA [3-tert-butyl-4-hydroxyanisole]), natural or synthetic, more or less hydro soluble, widely used as positive controls in the evaluation of the antioxidant activity (Moon & Shibamoto, 2009) were chosen to confirm that the decrease in agglomeration time of particles is related to a redox phenomenon. They were supplied by Sigma-Aldrich. The doses (0.06%, 0.2%, and 2% for Trolox, AA, and BHA, respectively) varied according both to their hydrosolubility (AA and Trolox hydrosoluble, at the opposite to BHA) and antioxidant capacity (minimal concentration to 50% reduce free radical DPPH: BHA<Trolox<AA) (Boulebd, 2020). They were diluted in the water used for dough hydration when hydro soluble or added as a powder at room temperature during mixing.

2.2.3   Particle size distribution of the dough after mixing. The agglomeration properties of durum wheat semolina and legume flours during mixing were evaluated under each mixing condition by sieving 100 g of the dough through 10 mm, 6.3 mm,

4 mm, 3.15 mm, 2 mm, and 1 mm mesh screens (Landillon et al., 2008). Particle size distribution have been analyzed through a classical approach, by reducing this distribution to discrete values as cumulative undersize centiles (D10, D50, D90). They represent the value of particle diameter (in mm) for which 10%, 50%, or 90% of the sample's mass had smaller diameter, respectively.

2.3   Pasta cooking properties

Pasta produced using native legume flours mixed at low temperature and using thermally pretreated legume flours were cooked for their respective optimum cooking times according to the AACC approved method (AACC, 1989). Cooking losses (%, db) were calculated as the difference between the dry matter of each dried and cooked pasta, relative to the dry matter of dried pasta. All the experiments were performed in triplicates. Pasta cooking loss was subjected to analysis of variance (two-way ANOVA) using "legume type" and "thermal treatment" as factors. ANOVA was followed by the Fisher's least significant difference (LSD) test

to compare means at the 5% significance level, using Statistica 8.0 software (Tulsa, OK, USA).

3. RESULTS AND DISCUSSION

3.1 Physicochemical and biochemical characterizations of wheat semolina and legume flours

Particle size distribution of wheat semolina and legume flours are listed in Table 1. With 90% particles smaller than 100 and 137 μm, faba bean and lentil flour particles are five times smaller than semolina particles whose diameter can reach 519 μm. The particle size of faba bean and lentil flours are very similar. Legume flours contain twofold more protein and four- to eightfold more fiber than semolina, whereas lipids are quite similar in the two types of raw materials. Lentils contain more proteins and fibers than faba bean (Table 1). Starch was 1.3- and 1.6-fold higher in wheat semolina than in faba and lentil flours, respectively.

3.2 Pasta processing

3.2.1 Hydration level and mixing time influence dough particle size and extrusion facility. The amount of water used for dough hydration was the main parameter that influenced the particle size of the dough during the mixing step. Table 2 lists the dough particle size obtained at each hydration level and each raw material after 20 min and/or 40 min of mixing on lab scale extruder. Durum wheat semolina was hydrated to 47% db for pasta making. The resulting wheat dough was mainly composed of small particles (D50 = 0.5 mm) or small aggregates (D90 = 2.2 mm) with no large pieces of dough (>4 mm). Petitot et al. (2010) reported 68% of dough semolina particles less than 1 mm and 30% between 1 to 4 mm with only 1.6% of larger pieces dough (>4 mm) in the same mixing and hydration conditions (20 min and 47%, on a dry basis, respectively).

Legume flours required less water to be hydrated than wheat semolina (Figure 1). This result was already observed when producing 35% legume (faba bean or split pea) enriched wheat pasta (45% water hydration from dry base for wheat-legume mixed dough against 47% for wheat dough) (Petitot et al., 2010).

When the percentage hydration of faba bean flour was increased from 37% to 42% (Table 2), after 20 min mixing, the particle sizes were close to those of wheat dough with a large proportion of small particles and small agglomerates (D10 ≤ 0.2 mm, D50 ≤ 1 mm and D90 ≤ 4 mm) with no large dough pieces (> 4 mm). Increasing mixing time from 20 to 40 min did not cause any change in the particle size when the hydration was less than 40% (results not shown); however, when hydrations were 40% and 41% (Table 2), the 40 min mixing period led to an increase in particle size with D10, D50, D90 reaching 0, 0.8, 3.6 mm for 41% hydration. Above 42% hydration, the size of particles increased whatever the hydration time (20 or 40 min) to reach 3.9, 7.5, 9.5 mm for D10, D50, D90, respectively with 44% hydration and 40 min mixing.

In the case of lentil flour (Table 2), after 20 and 40 min mixing, the dough still had a fine particle size with a D90 of less than 2.6 mm at 37% and 38% hydration, whereas 39% to 41% hydration led to a drastic change in the D50 and D90, which increased up to 7.1 and 9.5 mm. This means that, irrespective of the mixing time (20 or 40 min), 39% to 41% hydrated lentil doughs were mainly composed of large dough pieces (>4 mm) that are unsuitable for pasta making, rather than small agglomerates. The appearance of large dough lumps was already reported by (Petitot et al., 2010) in the case of 35% faba bean or split pea enriched wheat pasta, but was less pronounced (8% to 14% of particles >4 mm compared with more than 40% in our study on 100% legume pasta) probably due to the smaller proportion of legume flour used for substitution.

The agglomeration time (Table 2) was considered as the time when agglomeration of particle phenomenon starts. It was not observed during mixing, even during 40 min, when hydration was less than 43% for faba bean and less than 39% for lentil. At 43% and 44% hydration for faba bean, and as low as 39% hydration for lentil, the agglomeration time decreased drastically to reach, for example, 7 min for 41% hydrated lentil dough. This early appearance of large dough lumps hindered the extrusion step which starts after 20 min of mixing and need up to 40 min to be completed. This was especially true for lentil dough, which seemed to be more reactive than faba bean flour to agglomeration phenomena.

Concerning the extrusion step (Table 2), only faba bean and lentil that were from 37% to 42% and from 37% to 38% hydrated were successfully extruded at the lab scale, respectively. Higher hydration levels resulted in large dough lumps that could not be fed into the extrusion screw thereby hindering the extrusion step. Concerning the extruded faba bean dough, only one level of hydration (42%) resulted in an acceptable extrusion pressure ,that is, similar to that of wheat dough (1.172 × 10^7 Pa), rendering the scaling up of its production worthwhile. Lower levels of hydration (37% to 41%) led to very high pressure (>1.724 × 10^7 Pa) that locally heated the extruder screw, slowed down the extrusion process rendering it not available for industrial scale up. Lentil dough hydrated at a rate of 37% and 38% also led to very high extrusion pressure (>1.724 × 10^7 Pa) and were thus considered unsuitable for production at the pilot scale without modifying the process parameters. Higher hydration levels (39% to 41% dry base) led to very large dough lumps that hindered the extrusion process. Therefore, no possible range of hydration enabled processing of lentil flour into pasta at a satisfactory extrusion pressure.

3.2.2 Implication of enzymatic oxidation in the legume dough agglomeration phenomena. The alteration of legume dough formation, that is, the formation of large dough lumps previously demonstrated, and particularly rapid and extreme in the case of lentil flour, have been suspected to be due to a biochemical phenomenon such as enzymatic reactions. Indeed, we observed the release of steam and an increase in the temperature of the dough (>30 °C) during legume flour mixing. Lipoxygenase, a red-ox enzyme, could be involved, as large amounts have been already identified in legume flours with a range from 380 to 3,720 U/mg of flours for various legumes (Chang & McCurdy, 1985). Lipoxygenase is also known to be present only in very small amounts (<19 U/mg of flour) in the wheat semolina classically used to produce pasta (Permyakova, Trufanov, Pshenichnikova, & Ermakova, 2010), and for which no lump phenomena have been reported during pasta production. Our results, presented in Table 3, confirmed high lipoxygenase activity in both raw legume flours (415 and 435 U/mg for faba bean and lentil flours, respectively) that is 20 times the lipoxygenase activity of wheat semolina according to Permyakova et al. (2010).

In order to confirm the possible implication of lipoxygenase and more generally of enzymatic oxidation phenomena during the mixing step at room temperature, we investigated changes in antioxidant capacity and the effect of using antioxidants during the mixing of legume flours as they have been shown to inhibit lupin Lox activity (Jayasena, Leung, & Nasar-Abbas, 2010). Mixing experiments were performed in a lab scale extruder on 41% hydrated lentil flours as these are the most susceptible to agglomeration phenomena, as demonstrated above.

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Table 3–Lipoxygenase activity of the legume flours and agglomeration time[a] (min) on lab scale extruder affected by temperature mixing, thermal pretreatment of the flour, and addition of antioxydants.

Legume flour		Lipoxygenase activity[b] U/mg of the flour	% hydration (dry base)	Mixing: agglomeration time (min)[a]				
				Varying temperature		Adding Antioxidant		
				Room temperature	12–14°C	0.2% Ascorbic A.	2% BHA	0.06% Trolox
Native	Faba bean	415 ± 21	43	30[c]	> 40	ND	ND	ND
	Lentil	435 ± 22	41	7[c]	> 40	13	19	13
Thermally pretreated	Faba bean	35 ± 2	43	> 40				
	Lentil	35 ± 2	41	> 40				

[a]minimum time (precision ± 30 s) required for the appearance of dough lumps larger than 4 mm; > 40: implies no agglomeration of particles occurred during the 40 min mixing period.
[b]The standard deviation of the used methods is lower than 5%.
[c]values from Table 2.
ND, not determined.

Table 4–Production parameters of low temperature processed pasta at pilot scale.

Raw material	Mixing parameters (Hydration – T °C)	Dough particle size (mm)			Extrusion Pressure stabilization (× 10⁷ Pa)
		D10	D50	D90	
Faba bean	43% – 12 °C	0.0	0.9	3.2	1.034 to 1.379
Lentil	41% – 12 °C	0.3	0.9	1.6	1.241 to 1.517

The TEAC of the 41% hydrated lentil flour decreased by 63% after 7 min of mixing at room temperature (from 30.8 ± 0.3 to 19.6 ±0.4 mmol TEAC per kg). The addition of antioxidants such as ascorbic acid, BHA and Trolox, at the beginning of mixing slightly delayed the agglomeration phenomenon during mixing. The mixing agglomeration time increased from 7 min at room temperature to 13 min with ascorbic acid and trolox and 19 min with BHA (Table 3).

The variation in the TEAC of flours during mixing and the impact of the use of antioxidants on the agglomeration phenomena during mixing at room temperature confirm for the first time the occurrence of enzymatic reactions, notably redox, during the hydration and mixing steps, leading to agglomeration phenomena that prevent easy processing of legume pasta.

3.2.3 Low temperature mixing or thermal pretreatment of flours avoid an excessive legume dough agglomeration. To render the extrusion of both legume flours possible, we mixed legume flours hydrated to a level previously shown to lead to the formation of lumps under mixing at room temperature (43% for faba bean and 41% for lentil flour) on lab scale extruder and under different conditions intended to delay lipoxygenase biochemical phenomena.

A thermal pretreatment was applied to faba bean and lentil flours prior to mixing. Indeed, high temperatures (>70 °C) have previously been reported to be one of the ways to inactivate the lipoxygenase enzyme (Jayasena et al., 2010; Sun, Du, Jin, Liu, & Kong, 2012). Thermal pretreatment of lentil and faba flours led to a 12-fold reduction in lipoxygenase activity in both legume flours (Table 3). As shown in Table 3, thermally pretreated legume flours no longer agglomerated even after 40 min of mixing at ambient temperature instead of during only 7 and 30 min, for lentil and faba bean native flours, respectively.

The agglomeration time of legume flours was assessed when mixing on lab scale extruder at room temperature and at low temperatures (12 to 14 °C) likely to delay lipoxygenase reaction (Table 3). Low temperature mixing drastically delayed the agglom-

eration time for more than 40 min compared to 7 and 30 min for lentil and faba bean doughs, respectively. Reducing the mixing temperature therefore allowed the extrusion of the two legumes.

This is the first demonstration that either mixing at a low temperature or thermally pretreating legume flours facilitates the extrusion process of legume dough by delaying or avoiding oxidation phenomena through their action on the lipoxygenase present in the legume flours.

3.2.4 Scaling up of the low temperature pasta processing from laboratory to pilot extruder scale. Pasta made of 100% faba bean and lentil flours hydrated at a rate of, respectively, 43% and 41% (dry basis), were produced at pilot scale. The particle size distribution of the doughs was suitable for pasta production with D90 <4 mm even after 40 min of mixing (Table 4). The extrusion pressure varied between 1.034 and 1.517 × 10⁷ Pa, which was appropriate for the pilot pasta extruder used here.

3.3 Pasta cooking properties

The optimal cooking time and the cooking losses of pasta produced using native legume flours mixed at low temperature or using thermally pretreated legume flours mixing at room temperature on a lab scale extruder are presented in Table 5. The optimal cooking time of all pasta were not statistically different around 9.6 min. Legume pasta cooking time was also close to that of durum wheat pasta (9.3 min, Petitot et al., 2010). Legume pasta were compared to wheat pasta for their cooking losses. The very low value (i.e., 5.6%; Petitot et al., 2010) obtained for wheat pasta is primary due to the unique ability of gluten to form a strong protein network (Matsuo & Irvine, 1970). When using native legume flours mixed at low temperature, the pasta saw their cooking losses increased by 130% and 157% for lentil and faba bean flours, respectively. According to Laleg et al. (2016b), this is explained by the lack of strong covalent linkages in legume pasta, weakening the overall pasta structure facilitating therefore the leaching of material during pasta cooking. The increase of cooking losses of legume pasta in comparison to wheat pasta reached 368% and 264% when

Table 5–Cooking properties of pasta.

Pasta made from	Mixing temperature	Cooking time (min)	Cooking losses (%)
Native faba bean	12 °C to 14 °C	9.5± 0.17[a]*	14.4 ± 0.8[a]*
Native lentil	12 °C to 14 °C	9.8 ± 0.11[a]*	12.9 ± 0.1[a]*
Thermally pretreated faba bean	Room temperature	9.6 ± 0.5[a]	26.2 ± 2.6[b]
Thermally pretreated lentil	Room temperature	9.6 ± 0.4[a]	20.4 ± 0.6[c]
p-value	Effect of temperature treatment	0.7	0.000002
	Effect of legume flour	0.04	0.002
	Legume × temperature treatment	0.4	0.03

Values in the same column with the same letters are not significantly different.
*Previously published in Laleg et al. (2016b).

heat-pretreated faba bean and lentil flours were used, respectively. The use of low temperature mixing instead of flour heat pretreatment allowed a decrease of cooking losses of 45% and 37% for faba bean and lentil pasta, respectively. The higher cooking loss of pasta made from heat pretreated flours mixed at room temperature could be explained by the alteration of their constituents, notably proteins, during flour pretreatment. At the opposite, the mixing at 12 to 14 °C use for native legume flours could itself contribute to restrain the cooking loss of pasta by preserving dough components from oxidation and others modifications during mixing.

4. CONCLUSION

This work investigated the process parameters of 100% legume pasta production. We studied and solved the problem of agglomeration, previously described in the literature that leads to the formation of large sticky and gummy dough pieces during the pasta hydration and mixing step. This irreversible agglomeration of particles, which makes dough unsuitable for further extrusion, involves a biochemical red-ox phenomenon, notably the action of the lipoxygenase on legume flours. It can be delayed and even avoided with the use of a low temperature mixing or a thermal pretreatment of legume flours. For the first time, it opened the way to easily process 100% legume gluten free pasta on a standard pasta press, with interesting culinary and nutritional properties as characterized in detail in Laleg et al. (2016b). Low temperature mixing should be preferred as it makes legume pasta more resistant to cooking. Antioxidants could also be used at food safe levels in addition to thermal solutions.

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AUTHOR CONTRIBUTIONS

VM, KL, DC, and JA conceived and designed the experiments. KL, DC, and VM performed the experiments. KL, VM analyzed the data. KL and VM wrote the paper. VM acquired the funding.

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