Sustainable slices: Adding value to pea protein side streams in bread

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Sustainable Slices: Adding value to pea protein side streams in bread

Från sidoström till brödskiva: Värdeskapande av ärtproteinsidoströmmar

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Abstract

Efforts are being made to increase pea crops and pea protein production in Sweden. With protein production come side streams rich in fiber and starch. Simultaneously utilizing side streams by fortifying bread is increasingly popular. By fortifying white bread with pea protein side streams, the nutritional value of bread can be enhanced while reducing food loss. Known challenges of incorporating dietary fibers in bread make it highly interesting to evaluate pea protein side streams effect on baking properties. In this paper, white bread was fortified with two different side streams derived from different parts of the pea at varying concentrations and compared with a control white bread. The study was divided into two parts: a fresh bread study, where breads with varying side stream concentrations were analyzed for specific volume, color, moisture content, crumb structure (via image analysis), and crumb texture (via texture profile analysis) on day 1 after baking; and a shelf-life study, where specific volume, moisture content, and crumb texture were analyzed on days 1, 7, and 14, along with a sensory evaluation. Despite some technological challenges such as reduced volume and firmer crumb, consumer perception remained neutral, suggesting sensory acceptability at tested levels. This suggests that incorporating low levels of pea protein side streams can enhance the nutritional profile of bread without negatively affecting consumer acceptance. Further studies should explore the effects of higher dietary fiber concentrations and investigate the technological properties of starch and fiber in the side stream.

Keywords: Pea fiber, bread fortification, pea protein side streams, food industry by-products, dietary fiber.

Sammanfattning

Det pågår insatser för att öka odlingen av ärtor och produktionen av ärtprotein i Sverige. Vid proteinextraktion uppstår samtidigt biprodukter, så kallade sidoströmmar, som är rika på fiber och stärkelse. Att utnyttja dessa sidoströmmar genom att berika bröd har blivit allt vanligare. Genom att berika vitt bröd med sidoströmmar från ärtprotein kan brödets näringsvärde förbättras samtidigt som livsmedelsförluster minskas. Eftersom det är välkänt att kostfibrer kan påverka brödkvaliteten negativt, är det särskilt intressant att undersöka hur ärtproteinets sidoströmmar påverkar bakegenskaperna. I den här studien berikades vitt bröd med två olika sidoströmmar från olika delar av ärtan, i varierande koncentrationer och jämfördes med ett kontrollbröd utan fiber. Studien delades in i två delar: en färskbrödsstudie där bröd med olika nivåer av sidoströmsinblandning analyserades dag 1; samt en hållbarhetsstudie där specifik volym, vattenhalt och textur analyserades dag 1, 7 och 14 och ett sensoriskt konsumenttest utfördes. Trots vissa utmaningar, såsom minskad volym och fastare textur, förblev konsumenternas uppfattning generellt neutral, vilket tyder på sensorisk acceptans vid de testade fiberkoncentrationerna. Detta antyder att en låg inblandning av sidoströmmar från ärtprotein kan förbättra brödets näringsprofil utan att påverka konsumentacceptansen negativt. Framtida studier bör undersöka effekten av högre fiberkoncentrationer samt de teknologiska egenskaperna hos stärkelsen och fibrerna och stärkelsen i sidoströmmen.

Nyckelord: Ärtfiber, brödförstärkning, sidoströmmar från ärtprotein, livsmedelsindustrins biprodukter, kostfiber.

Table of content

List of tables

List of figures

List of abbreviations

BU	Brabender units
CS	Composite Side Stream made up of Fibradan shell fiber and Cosucra starch
CTRL	Control dough with 0 % side stream added
DF	Dietary fiber
IDF	Insoluble dietary fiber
LS	Lantmännen side stream made up of cotyledone fiber and starch
PFS	Pea fiber and starch
PPS	Pea protein side stream
RS	Resistant starch
SDF	Soluble dietary fiber
TDF	Total dietary fiber
WHC	Water holding capacity

1. Introduction

Plant proteins are playing a pivotal role in changing the global food systems, due to ethical reasons, health reasons and fighting climate change (Aiking & de Boer 2020; Kumar et al. 2022). The Swedish National Food Agency recently announced new dietary advice with sustainability also being taken in consideration: both regarding the foods direct environmental effect, and to increase national food security. Meat consumption is advised to be limited to 350 g/week and legume consumption is encouraged daily (Livsemdelsverket 2025). Efforts are being made in Sweden to increase pea crops and pea protein production. As a result of protein extraction, fiber- and starch-rich side streams are generated.

Simultaneously, one third of food is lost or wasted along the food chain, from agricultural production to final consumer (FAO 2011) contributing between 8-10 % of the world's greenhouse gas emissions globally (United Nations Environment Programme 2024) . Reducing food loss is critical for creating a more sustainable food system. According to the United Nations Sustainable Development Goal 12.3.1 (a) it is essential to "[...] reduce food losses along production and supply chains, including post-harvest losses" (United Nations Environment Programme 2024).

In the most recent national dietary survey carried out on the Swedish population, it was reported that most people consume bread daily, an average of two slices per day (Livsmedelsverket 2012) or an average of 76 kilograms per year (Jordbruksverket 2023). It was also found that only one in three Swedes meet the recommended fiber intake . Thus, white bread is a promising candidate for fortification with fiber-rich side streams. With growing interest in pea protein production, side streams follow (Ratnayake & Naguleswaran 2022). Fortifying bread with side streams is growing in popularity and is a promising strategy to reduce food loss is the repurposing of nutrient fiber rich by-products, by fortifying food products such as white bread, to both reduce waste and enhance nutritional value of bread (Tassoni et al. 2020).

Besides nutritional enhancement, dietary fibers have been shown to have technological benefits such as slowing the staling process in bread and increasing dough volume (Fadda et al. 2014; Jarosław Wyrwisz 2015). However, including side streams in bread has its' challenges as dietary fibers are known to impair technological as well as sensory properties of bread, such as volume and texture (Dalgetty & Baik 2006; Kurek & Wyrwysz 2015; Klava et al. 2024). Generally white bread is more liked by consumers (Bakke & Vickers 2007) making it challenging to incorporate dietry fibers(DFs). Therefore, it is highly relevant to investigate pea protein side streams' effect on baking properties in white bread.

1.2 Purpose and objective

The objective of this study was to evaluate the effects of pea protein side streams, derived from different parts of the pea, on bread quality parameters including volume, crumb structure, texture, and sensory properties. The results were compared with a control white bread. The purpose of the investigation was to explore the potential to increase the nutritional value of white bread while contributing to the reduction of food loss.

2. Background

2.1. Bread

Bread is a staple food consumed all over the world. Bread has been associated with the development of agriculture and domestication of cereals. Archaeological evidence has suggested that bread dating back as early as 14,000 years ago (Arranz-Otaegui et al. 2018). Bread comes in many shapes and sizes from diverse cultures around the world. The basics of bread baking involve mixing flour, water, yeast, and salt in appropriate ratios. Once gluten has been hydrated and subjected to mixing, the protein has the unique property to form a cohesive mass of dough and retain carbon dioxide gas (Cauvain 2003).

Bread quality is complex and influenced by ingredients, proportions, and processing methods. While definitions of "good bread" vary across cultures, gluten quality remains a key factor. Higher protein content generally leads to better gas retention and loaf volume (Cauvain 2003).

2.2. Dietary fiber

The EU regulation 1169/2011 defines DF as "*carbohydrate polymers with three or more monomeric units, which are neither digested nor absorbed in the human small intestine*". (EFSA Panel on Dietetic Products, Nutrition, and Allergies (NDA) 2010). A nutritional claim on food can imply, or state that the food contains beneficial nutritional properties. To claim that a food is "*high in fiber*" the food must contain at least 6 g/100 g of dietary fiber, and "*source of fiber*" must contain at least 3 g/100 g, according to EU legislation nr 1924/2006 (European Commission n.d.).

DF can be classified into insoluble dietary fibers (IDF) and soluble dietary fibers (SDF). IDFs act in the large intestine to promote fecal bulk and bowel movements while SDFs help regulate blood glucose levels and lower cholesterol in the small intestine (Rodréguez et al 2002). DF has well established health benefits with suggested effects of reducing a risk of the development of cardiovascular disease, type-2 diabetes and colon cancer (Phoertner & Fischer 2001; Wu et al. 2023).

2.3. Pea fiber and starch composition

Peas are a high-value protein based on their amino acid composition and functional properties (Shanthakumar et al. 2022). Furthermore, peas are a persistent crop that can grow in frost-hardy and cold climates (Tassoni et al. 2020) making it an appropriate crop for Swedish national food security and therefore efforts are being made to increase pea production in Sweden.

Fiber

Fortification of foods including bread, is increasing in popularity. DF adds nutritional value and is known to have technological beneficial properties such as extending the shelf life of bread due to the high water-holding capacity (Wyrwisz 2015; Klava et al. 2024).

Legumes consist of the hull (seed coat) and the cotyledon which in turn contains different types of DFs. Pea hulls are mainly composed of insoluble fibers like cellulose, hemicellulose, lignins and pectins (Phoertner & Fischer 2001; Klava et al. 2024) which are comparable to cereal bran

DF. Hull fibers are derived directly by dehulling and can be milled into different particle sizes. Pea cotyledon fibers can only be derived during an extraction processing of other components such as proteins, oils or starch (Phoertner & Fischer 2001).

The cotyledon is mainly composed of IDF (Phoertner & Fischer 2001; Wu et al. 2023) and contains mostly large amounts of non-starch polysaccharides (NSP), complex chains of sugars and uronic acids which are mostly IDF and are able to bind high amounts of water up to eight times their weight. These IDFs have high water-binding capacity and increase dough and bread yields. Further these IDFs can extend the shelf life of bread by reducing the staling process of wheat bread (Klava et al. 2024). However, the functionality of the fiber is of utmost importance and depends on their physiochemical properties and the processing conditions of the by-product (Klava et al. 2024). Fortification of bread with pea fiber can decrease the volume of bread, increase the water absorption of bread and decrease the overall quality of the bread (Dalgetty & Baik 2006; Kurek & Wyrwysz 2015) and pea hulls may also impact the sensory challenges by adding a pea aroma and taste (Klava et al. 2024).

Incorporating DF in bread dilutes the gluten matrix and disrupts gluten development which results in lower loaf volume due to decreased gas retention (Goméz 2002). Studies have shown that DFs can weaken the gluten network by competing with water needed for hydration of gluten proteins to build the gluten matrix. How fibers interact with gluten depends on their type, size, and how much water is available. Choosing the right kind of fiber, the right amount, and using proper mixing or pre-treatment methods can help reduce negative effects and improve bread quality (Zhou et al. 2021).

Starch

Starch is the primary storage carbohydrate in plants and is a major carbohydrate source (Wang et al. 2011), making up an average of 50 % of the caloric intake if a western diet (Wang et al. 2015). Starch is made up of lightly branched amylose and highly branched amylopectine (Wang et al. 2015). Depending on the cultivar, pea starch has been shown to range between 30 ~60 % amylose content (Wang et al. 2022). Starch contributes to staling of bread which can cause reduced shelf-life and food waste, more specifically due to the retrogradation of amylopectin. Starch retrogradation involves rapid recrystallization of amylose and slow recrystallization of amylopectin (Fadda et al. 2014).

Peas are rich in starch which makes up approximately 39-46 % of the pea and contain high amylose content which is associated with and increased resistance to digestion thus lower glycemic index. Peas also contain significant amounts of resistant starch (RS), up to 7 % which are regarded as an important DF (Wu et al. 2023).

2.4. Analytical methods

2.4.1. Farinograph

The farinograph is an instrument used to measure the change of consistency in dough by measuring the resistance of the dough against rotating mixing blades. The dough is mixed in a temperature-controlled mixing bowl and the resistance is measured and recorded graphically in a so called “Farinogram”, as Brabender Units (BU) versus time. The farinograph can be used to measure water absorption amongst other dough parameters.

2.4.2. Texture profile analysis

Texture is an important sensory property of bread along with taste and appearance and will often determine if the product will be purchased. Texture is also an important factor regarding the freshness of the bread like crumb hardness increasing over time due to starch retrogradation (Young 2012).

Textural profile analysis (TPA) is a test used to imitate the action of the jaw when biting into a food. The principle of TPA involves placing a bite-sized food sample on a baseplate and compressing the sample twice with a probe, resulting in a force-time curve that can be converted to different textural parameters (Bourne 2002). A force-time curve can be obtained from textural profile analysis (see figure 1) and textural parameters such as hardness, springiness and cohesiveness can be obtained (Cauvain 2003).

Hardness is the force needed for deformation (Szczesniak 1963) and is defined as the force peak of the first compression (Bourne 2002). The first peak is defined as hardness (Figure 1a).

Cohesiveness refers to how well the crumb holds together during chewing ad is usually a desired train which is affected both by moisture content and the strength of the crumb structure (Young 2012 – chapter 22). Cohesiveness is the ratio of the positive force areas under the first and second compressions (Bourne 2002) (Figure 1b and 1c).

Springiness refers to how well the crumb of the bread bounces back to its original shape after being pressed, which tends to decrease as the bread stales (Young 2012). Springiness is defined by the rate at which a deformed material returns to its original condition (Szesniak 1963) as the time passed between the end of the first bite and the starch of the second bite (Bourne 2002) sh(Figure 1d and 1e).

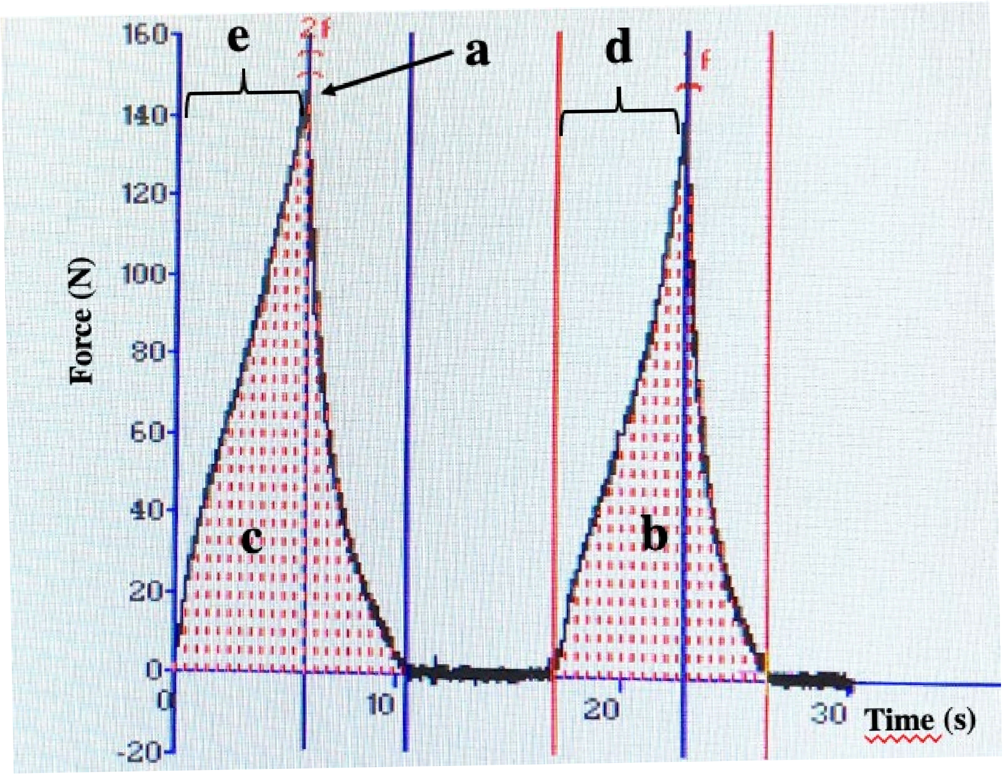

Figure 1. A typical force-time curve obtained from TPA of bread. a: peak force of the first compression, b: area of the second compression, c: area of the first compression, d: time distance of the second compression, e: time distance of the first compression.

Table 1. Textural parameters definitions.

Textural parameter	**Physical definition** (Szczesniak 1963)	**Sensory definition** (Bourne 2002)	**TPA definition** (Bourne 2002)	**In Figure 1**
Hardness	The force necessary to attain a given deformation	Force needed to compress food between molars	Peak force value of first compression	a
Cohesiveness	The strength of the internal bonds, making up the body of the product.	Extent of compression of food between theeth before rupture	Ratio between positive force areas of second and first compression	b,c
Springiness	The rate at which a deformed material goes back to its underformed condition after the deforminf force is removed	Degree of recovery to originatl shape after compression between teeth	Recovered height of the sample between the two compressions	d,e

2.4.3. Color measurement

Color of the bread crust and crumb can be measured as a sensory and textural attribute of bread (Young 2012). The Lab color system is an objective system of quantifying color. L*:lightness on the scale of 0=black to 100=white, a*: red-green axis on which positive=red and negative=blue, and b*: the yellow-blue axis on which positive=yellow and negative=blue (Lawless & Heymann 2010).

2.4.4. Crumb structure by image analysis

Image analysis can be used to assess the bread crumb by analyzing the cell count, average cell size and cells per area (area percentage) (Young 2012). ImageJ is an open-source software, distributed by FIJI, widely used for biological image analysis (Schindelin et al. 2012). Digital software analysis can be used for breads and other baked products and provide objective understanding of bread texture (Cauvain 2020b; Rahimi et al. 2020).

2.4.5. Sensory evaluation

Sensory evaluation is important for the industry to evaluate products before large scale-manufacturing and involves the evaluation a product by all five senses: sight, smell, taste, touch and sound. Consumer opinions are important for producers for it is their opinion that makes or breaks a product when it reaches the market. Sensory evaluation can be divided into affective and analytical tests where affective testing is subjective and analytical is objective (Gustafsson et al. 2014) . Acceptance tests measure the liking or preference of a product and can be used for two or more products. The test can be used to compare which product is best liked, i.e. preferred, which can be done by forced-choice. Because of the direct relationship between the liking/acceptance and preference, this can also be done indirectly by determining which products scored higher by consumers (Stone et al. 2021).

Consumer tests can be carried out in different types of locations and there are different advantages and disadvantages with different locations. Laboratory tests provide controlled environments and specific target groups can be invited to participate (Gustafsson et al. 2014). Testing performed in a public place such as schools or malls provide and easy way to reach many people however, preparation of food samples may be more complicated and finding an undisturbed environment can be hard (Gustafsson et al. 2014). For tests performed in public locations, approximately 100 or more responses are usually collected (Stone et al. 2021).Home testing is also an alternative which provides the most realistic environment for the products consumption. There is however less control over how the test is performed when this is left entirely up to the consumer (Gustafsson et al. 2014).

The hedonic scale is widely used to evaluate all kinds of different foods and useful in liking and preference testing. It is easy to understand with simple instructions and provides stable results both in liking and reproducible results in different target groups. The results of a hedonic scale (Table 2) can show liking of a product which also can be interpreted as the preference of the products. The responses can be analyzed with a Student's t distribution or t-test which is a popular statistical analysis method for such sensory evaluations (Stone et al. 2021).

Table 2. An example of the 9-point hedonic scale.

Score	Liking
1	*Like extremely*
2	*Like very much*

3	*Like moderately*
4	*Like slightly*
5	*Neither like nor dislike*
6	*Dislike slightly*
7	*Dislike moderately*
8	*Dislike very much*
9	*Dislike extremely*

3. Materials and Method

3.1. Materials

'Extra bagerivetemjöl' (wheat flour intended for baking) was provided by Lantmännen (Sweden). The protein content was 12 g/100 g and the fiber content was 3.5 g/100 g, as per the nutritional information. Moisture content was measured to 9.07 %. Pea side stream was provided by Lantmännen (Sweden) which consisted of approximately 40 % fiber and 60 % starch derived from the pea cotyledon. The composite side stream was produced by mixing 40 % pea fiber (Fibradan® F20X, Vestkorn, Sweden) and 60 % pea starch (NASTAR™ native pea starch, Cosucra, Belgium) to represent the LS. Fibradan® consisted of fiber derived from pea hull, moisture content was measured to 10.47 %. NASTAR™ Cosucra pea starch, with 48 % amylose content measured to 8.16 % moisture content. Wheat gluten (Hvedegluten, Bagerens, Denmark) was purchased online, containing 75 % protein. The moisture content of the gluten powder was measured to 7.07 %. Microencapsulated sorbic acid (MIRCAP® SB85-G) was provided by Lantmännen.

Additional ingredients were purchased at the local shop; rapeseed oil (Eldorado rapsolja), dry yeast (Jästbolaget, Kronjäst, Sweden), sugar (ICA Strösocker, Europe), salt (Falksalt med jod). One new dry yeast package, from the same production batch, was opened on each day of experiments to ensure that the yeast quality did not vary.

The side stream provided from Lantmännen derived from pea cotyledon will be referred to as LS in this paper. The composite side stream which was produced by mixing commercial fiber and starch will be referred to as CS.

3.2. Experimental design

This study used an experimental design made up of control type and two independent crossed factors: (1) Side stream type with two levels: side stream from Lantmännen and a created 'composite side stream' with the same fiber-to-starch ratio), and (2) Side stream concentration tested at different levels. Each dough type and control dough was made in duplicates and breads were analyzed in triplicates.

A secondary experiment was also carried out and breads were baked for a consumer test and shelf-life study. 2 % concentration of added fiber was chosen as 2 % LS showed the best baking properties out of LS, especially regarding specific volume. The purpose of the sensory analysis was to explore the possibility of incorporating LS in bread and whether this would be accepted by the consumers as white bread. CTRL, 2 % CS, 2 % LS were baked in duplicates and breads were analyzed in triplicates for the shelf-life study.

3.3. Dry ingredients' moisture content

The moisture contents of the dry ingredients (Lantmännen wheat flour, Lantmännen pea side stream, gluten, Fibradan, Cosucra) were determined gravimetrically at 105 °C overnight, for at least 18 h.

3.4. Starch analysis

Resistant starch analysis was mainly performed by the supervisor. Samples analyzed for the purpose of this paper were: Wheat flour, Lantmännen side stream, Fibradan, Cosucra, and GP. Further, resistant starch was measured on shelf-life breads 2 % CS, 2 % LS and CTRL on day

1, 3 and 7. Resistant starch was analyzed using the Megazyme Resistant Starch Rapid kit according to AACC Method 32-40.01 and AOAC Method 2002.02.

3.5. Water holding capacity and oil holding capacity

Water holding capacity (WHC) was determined by centrifugation (Robertson et al. 2000). Side stream samples (LS and CS) were analyzed in triplicates by hydrating 3,0 g of sample in 30 ml deionized water in 50 ml Falcon tubes (Falcon tube 50 ml, VWR) for 24 h at room temperature. The samples were centrifuged (3000 x g, 20 min and 10 000 x g, 30 min) and the supernatant was decanted. The fresh sample weight was recorded prior to drying at 105 °C for 18 h. The WHC was calculated as:

$$WHC = \frac{(m_1 - m_2)}{m_2}$$
$$m_1 = weight\ of\ wet\ pellet$$
$$m_2 = weight\ of\ dry\ pellet$$

Oil holding capacity (OHC) was determined based on the method according to (Cheng et al. 2022). Side stream samples (LS and CS) were analyzed in triplicates by weighing 3,0 g sample and 30 ml rapeseed oil in 50 ml Falcon tubes (Falcon tube 50 ml, VWR) for 24 h at room temperature. The samples were centrifuged (10 000 x g, 30 min) and the supernatant was decanted. Oil-soaked sample weights were recorded and OHC was calculated as:

$$OHC = \frac{m_{oil}}{m_0}$$
$$m_{oil} = weight\ of\ oil\ soaked\ pellet$$
$$m_0 = weight\ of\ dry\ sample$$

3.6. Assessment prior to baking

First, baking trials were made to assess appropriate levels of fiber to add based on specific volume and tactile dough assessment by the baker. 2 %, 3 % and 4 % added fiber was chosen as levels of fiber added for the experimental design.

Baking trials were also made to assess appropriate amounts of water and mixing times for chosen levels of added fiber and (2%, 3%, 4 %, and 0% CTLR). During these initial trials, doughs were mixed to reach an approximate consistency of 480 Brabender Units (BU). Added amounts of water can be seen in Table I in appendix I.

3.7. Bread making

The farinograph was turned on approximately one hour before the experiment to ensure the temperature was at 30 °C from start. Bread was made according to the straight dough system also known as no time dough or rapid dough. The method entails mixing all the dry ingredients and water until the dough reaches appropriate consistency decided by the baker (AACC 10-10B).

Flour was calculated to the equivalent to 300 g (14 % moisture basis) and side streams (CS ans LS) were added at three concentrations (2 %, 3 %, 4 % dwb) by replacing flour. Water was added to uphold the consistency of 480 BU and gluten added to doughs with side streams to keep a constant protein content.

All the dry ingredients were added to the bowl of the farinograph and mixed for approximately 1 min. Dry yeast was added to the flour 10 min prior to start to activate the yeast, according to the packaging. Water was added until 480 ± 20 BU and the mixing time was predetermined until peak dough consistency. The dough was proofed for 1 hour under a tea towel in a lightly greased bowl for at 38 °C ± 2 °C with 50 % relative humidity. Each dough was divided into four 100,0 g dough balls and shaped in an extensograph with 20 rotations. Shaped doughs were placed in lightly greased tins and proofed for 45 min at 38 °C with 50 % relative humidity. Bread loaves were baked for 9 min at 250 °C with steam for the first 5 seconds of baking.

The doughs were prepared in duplicates from which four loaves were baked and cooled for three hours before being put into resealable plastic bags. Three loaves were analyzed on day 1 after baking.

3.8. Bread measurements

Specific volume, TPA, scanning, and color measurements were done on day 1 after baking. The loaves were cooled to room temperature for 3 h before placement in plastic bags for storage until the next day for analysis. All analyses were additionally performed after day 1, 7, and 14 on breads prepared in stand mixer for the shelf-life study.

3.8.1 Specific volume

Specific volume was determined by the seed displacement method and specific volume was expressed as the volume of the loaves divided by the weight of the loaf (ml/g).

3.8.2. Texture profile analysis

Texture analysis was performed according to AACC Standard method 74-09 (Determination of Bread Firmness). Each loaf was cut into a 12.5 mm slice and two slices were stacked on top of each other for analysis. A 36 mm aluminum cylinder probe was used with test speed 1.7 mms^{-1}, compressed in two cycles to 40 % of its’ height.

3.8.3. Crumb structure by image analysis

Image analysis was done by scanning images in a print scanner (Ricoh IM C5500) and scanned JPEG images were analyzed in the open-source software ImageJ. Each photo was cropped to capture only the bread slice. The photos were then converted into 8-bit format and segmented using auto threshold Percentile mode. The photos were then processed, using binary watershed and total cell count, cell size and area percentage was measured.

Figure 2. Example of crumb structure by image analysis. Left photo of scanned bread slice prior to image processing and right photo after image processing in ImageJ.

3.8.4. Moisture content

Moisture content was determined gravimetrically by sampling circular cut out pieces of bread in triplicates from one slice of each three bread loaves. The cut outs were taken from the crust, crumb, and bottom of each slice as seen in image 3.

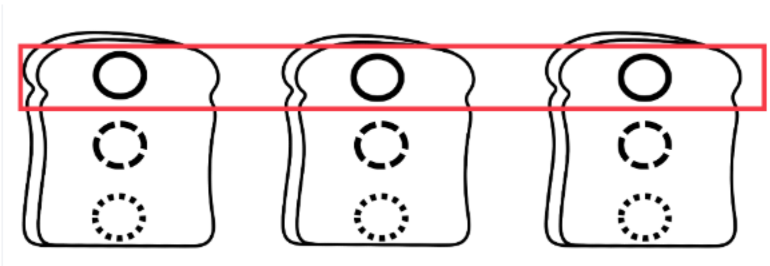

Figure 3. Image of how moisture content was measured. Three cut outs from top crust, crumb, and bottom crust were taken from three bread slices in each dough type.

3.8.5. Color analysis

Minolta Chroma meter CR-300 (...) was used to measure the bread crust and crumb in the L*a*b* color space. Each of the three loaves per dough duplicate was measured on the crust of intact bread and then on the crumb of sliced bread in triplicates.

3.9. Sensory evaluation and shelf life

Three bread types were prepared for the consumer test: 2 % LS, 2 % CS and CTRL, as 2 % LS showed the best results regarding baking properties, especially regarding specific volume.

Doughs were baked in a stand mixer (Electrolux Mod. 8., 220 V, 400 W) to yield larger dough volumes for consumer tests and shelf-life experiments. The recipes used in the experimental design (Table II, Appendix II). All the dry ingredients were added to the bowl of stand mixer and mixed for approximately 1 min. Dry yeast was added to the flour 10 min prior to start to activate the yeast, according to the packaging. Water was added according to the upscaled recipes, and the doughs were mixed until a gluten window could be formed by the baker.

The dough was proofed for 1 hour under a tea towel in a lightly greased bowl for at 38 °C ± 2 °C with 50 % relative humidity. Each dough was divided into 16 dough balls of 100.0 g that were shaped in an extensograph with 20 rotations. Shaped doughs balls were placed in lightly greased tins and proofed for 45 min at 38 °C with 50 % relative humidity. Bread loaves were baked for 9 min at 250 °C with steam for the first 5 seconds of baking.

Nine bread loaves, three for each analysis day, were placed in resealable plastic bags and stored for 1, 7, and 14 days. Doughs were baked in duplicate, and breads were analyzed in triplicate in the same way as the experimental design. The remaining seven bread loaves were placed in a resealable plastic bag in the freezer and stored until the consumer test. The bread loaves were thawed at room temperature the evening prior to the consumer test.

On the day of the consumer test, 16 rectangular pieces of bread were cut from the crumb of each loaf, and two samples of each bread type were packed in plastic bags labeled with random three-digit codes (Table VI, Appendix VI). Samples were handed out with a QR-code, connected to a digital survey (NETIGATE) with questions (Table XI, Appendix VI) regarding the liking, and motivation of liking and preference, of the bread types. Six different QR-codes were prepared to ensure a balanced sample serving. Each QR-code instructed a different order of testing of the three-digit coded samples. A total of 100 samples were handed out to students and staff working at Campus Ultuna, Uppsala.

3.10. Statistical analyses

Minitab 19 was used to perform one way ANOVA using Tukey's pairwise comparisons and Dunette comparison to control was performed on each measured parameter presented in the study. R was used to create tables. Sensory analysis data was analyzed using a two-sample t-test (type 3: unequal variances) to identify significant differences between samples and consumer groups in Excel. A result processing table for Chi-square values was used for sensory analysis. All statistical analyses were conducted at a 95% confidence level.

4. Results and discussion

4.1. Raw material analysis and dough consistency

4.1.1. Water holding capacity and oil holding capacity

LS showed both water holding capacity (WHC) and oil holding capacity (OHC) compared to CS in accordance with Phoertner & Fishcer (2001) showing twice as high WHC in pea cotyledon fibers compared to pea hulls. High water holding capacity is a desirable trait in the food industry as it increases dough volume (Fadda et al. 2014).

Table 3. Water holding capacity of side stream samples expressed in grams of water per gram of solid sample. CTRL=control bread without side stream, CS = composite side stream with fiber derived from pea hull, LS = Lantmännen side stream derived from pea cotyledon.

Sample	WHC (g water/ g)	OHC (g oil/g)
LS	6.7 ± 0.9	3,5 ± 0
CS	1.6 ± 0.2	2,6 ± 0

4.1.2. Total dietary fiber content of bread

Table 4 refers to the total dietary fiber content (TDF) of the bread. The dietary concentrations chosen for the experimental design were partially based on estimations to obtain bread that could be claimed as a source of "high in fiber" i.e. 6 g/100 g of bread. DF content was estimated by adding the amount of fiber from added side stream and wheat flour (dwb) and accounting for water lost in the oven. TDF content was calculated by adding the addition of fiber from side streams and fiber content in the flour, as well as the analyzed RS content. RS was measured on shelf-life breads, therefore values are only given for CTRL and 2 % fiber addition.

None of the bread types obtained high enough TDF to claim "high dietary fiber" however all bread types, obtained high enough TDF to claim "source of fiber" which is 3 g/100 g (European Commission n.d.).

Table 4. Estimated fiber content in bread.

Dough type	Fiber added (%)	Calculated DF dwb in bread without RS	Calculated TDF bread dwb, including RS
CTRL	0	2.2	3.3
2 % CS	2	3.3	4.5
3 % CS	3	3.9	
4 % CS	4	4.5	
2 % LS	2	3.1	4.4
3 % LS	3	3.5	
4 % LS	4	4.0	

4.1.3. Dough consistency and amount of added water in dough

The blue circles representing water added in figure 4 clearly visualize that higher amounts of water were required for LS-fortified doughs to obtain similar dough consistency as CS and

CTRL during dough preparation. This is in line with results shown in previous studies where pea cotyledon fibers have had higher water absorption capacity (Dalgetty & Baik 2006). This further aligns well with the results above showing that LS had higher water holding capacity as seen in Table 3 in section 4.1.1. Higher WHC in dough could be seen as a positive technological property as it increases dough volume (Fadda et al. 2014), which would be good from an industrial point of view.

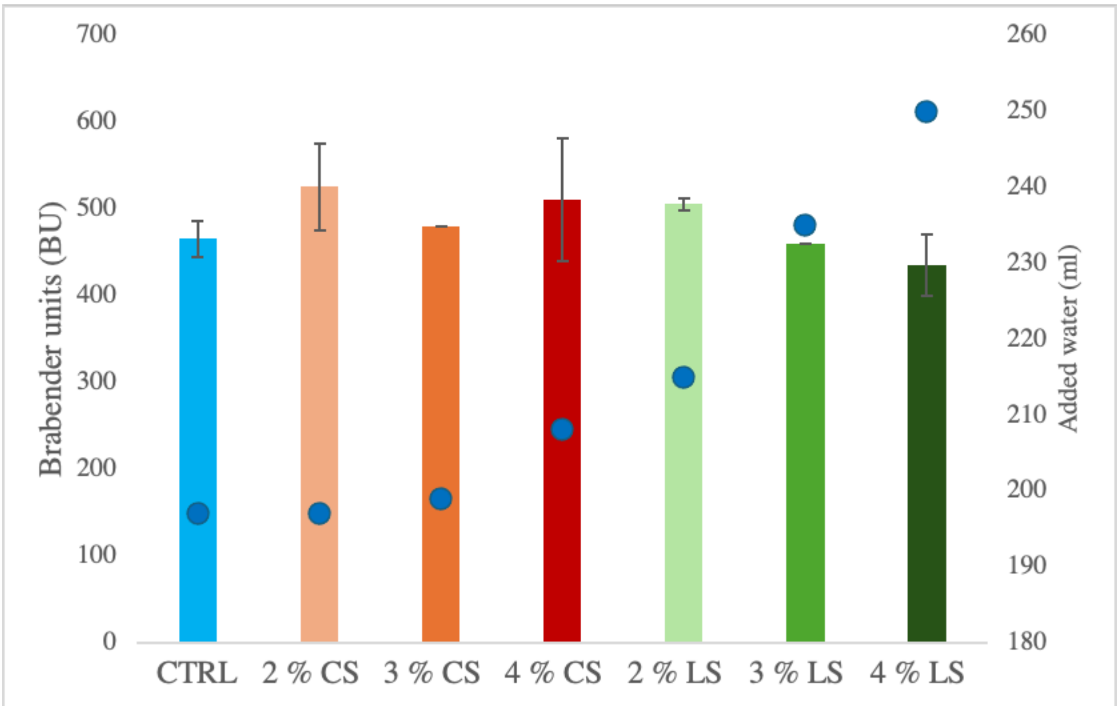

Figure 4. Dough consistency (BU) on left y-axis and added amounts of water (ml) shown as blue circles on respective column corresponding to the secondary, right y-axis. CTRL=control bread without side stream, CS = composite side stream with fiber derived from pea hull, LS = Lantmännen side stream derived from pea cotyledon.

4.2. Fresh bread results and discussion

The loss of volume can be seen with the naked eye as seen in figure 5. The cause of this will be discussed further in this section of fresh breads baked for the original experimental design which includes three levels of added fiber from two side streams, LS (derived from the cotyledon) and CS (derived from the hull), and CTRL (without added fiber).

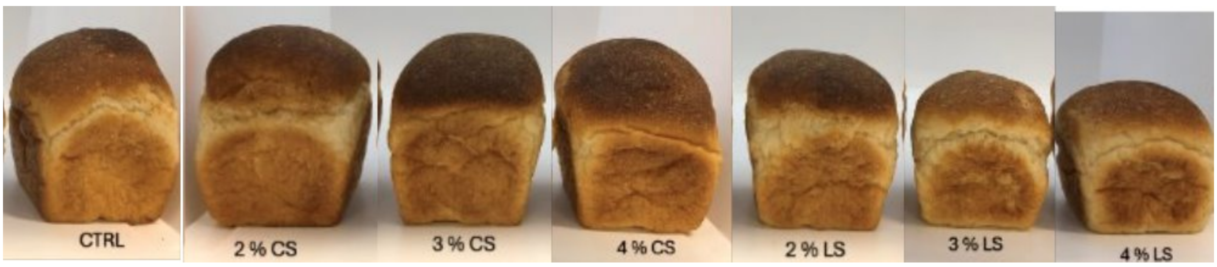

Figure 5. Breads baked for experimental design with different fiber types and concentrations. From left to right: CTRL, 2 % CS, 3 % CS, 4 % CS, 2 % LS, 3 % LS, 4 % LS. CTRL=control bread without side stream, CS = composite side stream with fiber derived from pea hull, LS = Lantmännen side stream derived from pea cotyledon.

4.2.1. Color

One important parameter for consumers' acceptance of a product is the color (Niño-Medina et al. 2019). In bread, a golden-brown crust and a creamy white crumb are desired (Kurek and Wyrwisz 2015).

There was no significant difference in crust color regarding L* (lightness), a* (+red/–green) or b* (+yellow/–blue) in neither bread type. This in contrast to previous studies that have shown the pea fiber fortification darkens the crust of breads, due to Maillard reactions (Dalgetty & Baik 2006; Gomez et al. 2002; Niño-Medina et al. 2019)

While the color of the crust is influenced by Maillard reaction, the crumb color of bread is usually associated with the color of the ingredients (Goméz et al. 2002). Regarding L* (lightness) only 4 % CS was significantly lighter than the other breads. There were significant differences were found in the crumb in which all six concentrations of fiber side streams increased redness. CTRL was the least red (–9.5) and 4 % LS was the reddest (–8.6) which agrees with results from a previous study where addition of pea hulls darkened the crumb and increased redness (Klava et al. 2024). The crumb of 2 % LS, 4 % LS were significantly more yellow compared to CTRL, however, did not increase the color consistently with the addition of fiber.

Even though there was a slight increase in redness by the addition of fiber and two levels of LS showed an increase of yellowness, there was no difference in color between the breads to the naked eye. This is positive in the aspect of consumer acceptance (Niño-Medina et al. 2002) and the potential with PPS fortification of bread.

Table 5. Average color of crust and crumb. Different letters in the same column indicate significant difference at 95 % confidence level.. CTRL = without fiber, CS = fiber derived from hull, LS = fiber derived from cotyledon.

	Color					
	L* (lightness)		a* (+red/–green)		b* (+yellow/–blue)	
Doughtype	**crust**	**crumb**	**crust**	**crumb**	**crust**	**crumb**
CTRL	41.6 a	69.3 a	8.7 a	-9.5 d	32.1 a	35.8 bc
2 % CS	43.8 a	70.1 a	9.3 a	-9.1 c	34.2 a	36.7 ab
3 % CS	43.3 a	69.7 a	9.0 a	-9.1 c	33.2 a	36.4 ab
4 % CS	46.1 a	63.6 b	8.0 a	-9.1 c	32.1 a	35.2 c
2 % LS	44. 0 a	70.2 a	9.2 a	-9.0 bc	34.2 a	36.8 a
3 % LS	44.1 a	68.9 a	9.0 a	-8.7 ab	32.9 a	36.4 ab
4 % LS	45.3 a	70.2 a	9.4 a	-8.6 a	35.5 a	37.2 a

4.2.2. Specific volume

Figure 6 shows that bread fortified with LS (fiber derived from cotyledon fiber) resulted in breads with significantly lower specific volume compared to CS breads and CTRL. The specific volume also significantly decreased within the bread type with higher levels (4 % LS) of added fibers.

Fortification of wheat bread with pea fibers is known to reduce loaf volume and create denser bread structure due to fibers weakening gluten networks and thus lowering gas retention of bread (Klavae et al. 2024; Goméz et al 2022; Dalgetty & Baik 2006). One reason for weakened gluten network is due to the dilution of gluten in the dough while replacing flour with other fortification ingredients (Goméz et al. 2022). For this reason, gluten was added to the recipe in accordance with the amount of estimated protein lost from replacing flour with side stream.

Another reason for impaired gluten network is that fibers compete with gluten proteins for water which is necessary to create the gluten matrix which in turn is necessary for gas retention in the bread (Zhou et al. 2021). This could align with the fact that LS had higher water holding capacity as shown in Table 4 and that higher amounts of water were necessary to be added to obtain the same dough consistence for LS compared to CTRL and CS (figure 4). This would then also be seen in the crumb structure as gas bubbles would collapse and coalesce, thus creating lower cell count, more on that in the section 4.2.2. – Crumb structure by image analysis.

Dalgetty & Baik (2006) showed that loaf volume generally decreases with the addition of both pea hulls and cotyledon fiber. At the same level of substitution there was a larger volume decrease in bread fortified with cotyledon fibers compared to hull fiber and further that insoluble cotyledon fibers decrease bread volume more than soluble cotyledon fibers. Bread fortified with 5 % pea hull resulted in lower volume compared to control bread without addition of fiber, meanwhile breads fortified with insoluble and soluble cotyledon fibers resulted in even lower volume.

The decrease in specific volume shown in figure 6 aligns with Dalgetty & Baik (2006) in the fact that LS (derived from cotyledon) decreased specific volume more than CS (derived from hull). As there was no significant difference between CS and CTRL, it is important to remember that LS and CS also contain 60 % starch which has an impact on gluten and water interactions in the dough and will have a final impact on the bread.

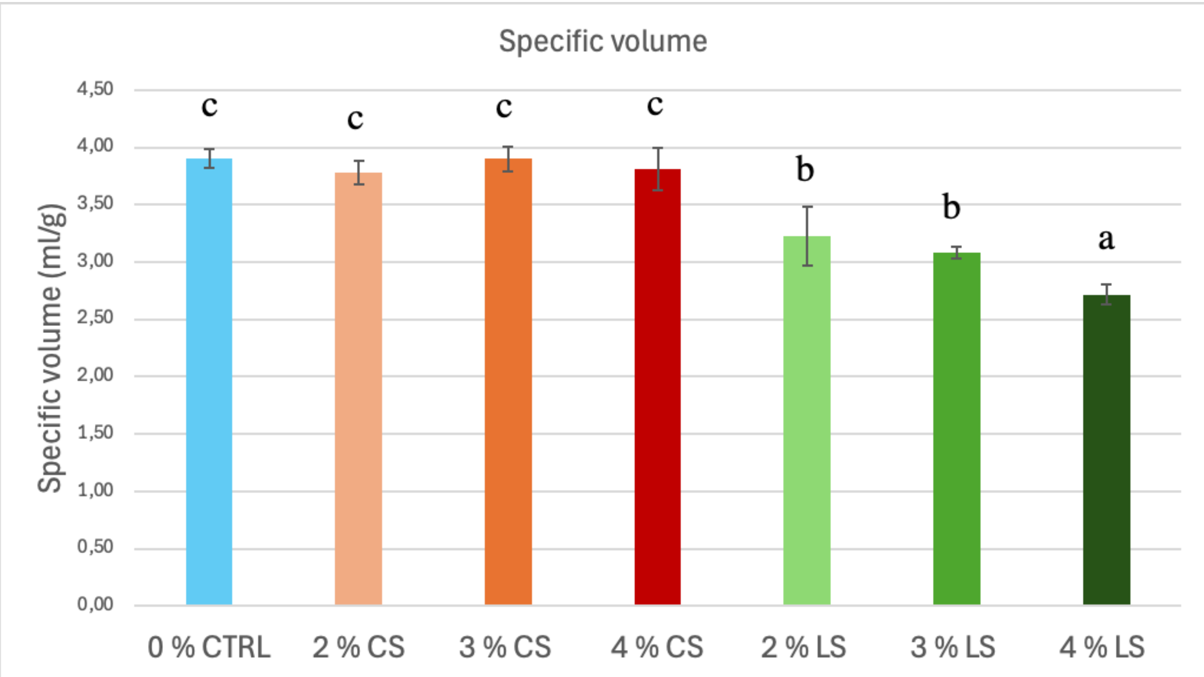

Figure 6. Average specific volume (ml/g) of breads baked from doughs in experimental design. Each dough is baked in duplicates and bread loaves are measured in triplicates from each dough. Different letters above the columns indicate varians between the dough types at p<0,05.

4.2.3. Crumb structure by image analysis

2% LS had a significantly lower cell count compared to CTRL which would suggest impaired gas retention or increased bubble coalescence (Cauvain 2015). As discussed above, this could be supported by the fact that LS has a much higher WHC that could be competing with gluten proteins and impairing the gluten network. LS shows lower cell count in all concentration levels; however, this trend of lower cell count is not statistically supported. This could still support the suggestion that the high WHC could impair the gluten network and further impair gas retention and thus explain the decrease in specific volume.

As this hypothesis is not supported by statistics, the method of image analysis or thresholding settings could perhaps explain the non-significant results. However, the scanned images in Figure I, Appendix IV do not show any outstanding differences that would imply so. There was no significant difference between the dough types regarding average size or area percentage of the crumb structure of the breads.

Previous study has found breads fortified with soluble cotyledon fibers to produce more uniform crumb structure compared to insoluble fibers and hull fibers (Dalgetty & Baik 2006). In this experiment, there were generally no significant differences in crumb structure between breads compared to CTRL.

Table 6. Average cell count, cell size and area percentage from scanned bread slices.

	Cell count	**Average cell size**	**Area percentage**
CTRL	1937.7 a	123.3 a	26.6 a
2 % CS	1788.0 ab	118.4 a	23.5 a
3 % CS	2080.0 a	116.3 a	27.1 a
4 % CS	1671.3 ab	124.4 a	23.0 a
2 % LS	1591.0 b	182.0 a	28.8 a
3 % LS	1698.0 ab	132.8 a	24.8 a
4 % LS	1917.3 ab	124.5 a	26.4 a

4.2.4. Moisture content

Moisture migration leads to a firmer crumb and a softer crust during storage by contributing to the staling of bread as amylopectin undergoes retrogradation (Young 2012 chapter 23). To delay the staling of bread, high moisture content is desired in bread (Cauvain 2015).

Table 7 shows that there is generally no significant difference in moisture between CS (derived from pea hull) and CTRL bread. LS (derived from cotyledon fiber) has significantly higher moisture content in all parts of the bread when compared to CTRL (Table 7) suggesting LS being a promising candidate to fortify bread in respect of prolonging bread shelf life (Niño-Medina et al. 2019; Cauvain 2020a; Klava et al. 2024). The moisture contents of the breads were analyzed on day 1 after baking and breads were stored at room temperature. (Dalgetty & Baik 2006) showed that pea hull and insoluble cotyledon fibers, both retained moisture in bread during seven days of storage, therefore what is more interesting is to see how LS and CS retain moisture over time which is discussed and analyzed in section 4.3.2 – Mositure over time.

Table 7. Average moisture content in top crust (MoistureT), middle crumb (MoistureM), and bottom crust (MoistureB) measured on day 1. Different letters within the same column indicate significant differences with 95 % confidenc.

	MoistureT	MoistureM	MoistureB
CTRL	37.0 a	43.3 ab	41.3 a
2 % CS	37.2 a	43.0 a	41.0 a
3 % CS	37.5 ab	42.8 a	40.9 a
4 % CS	36.9 a	43.2 ab	42.2 ab
2 % LS	40. b	45.2 bc	44.1 b
3 % LS	43.9 c	46.4 c	47.0 c
4 % LS	44.9 c*	49.4 d*	48.2 c*

4.2.5. Texture profile analysis

Figure 7 shows there was no significant difference in hardness between the dough types except for 4 % LS. This would suggest that fortification with these pea protein side streams (PPS) (LS and CS) generally do not have an impact on crumb firmness at low concentrations, under 5 % fiber addition. This was shown by Dalgetty & Baik (2006) in a study which concluded that generally fortifying bread with <5% of pea hulls and cotyledon fibers did not increase the bread hardness which is in line with the results in this experiment.

However, while comparing the dough types with Dunett multiple comparisons with CTRL, all three concentrations (2 %, 3 %, 4 %) of LS are significantly harder compared to CTLR in the experimental design. This could align with a study, contrary to previous results by Dalgetty & Baik (2006) showing that incorporating pea fiber at concentrations as low as 2 % increase crumb firmness (Gomez et al. 2001).

Fortifying bread with fiber is known to delay bread staling and slow down the crumb firmness over time (Cauvain 2020) and more specifically for pea fibers due to their moisture retention (Dalgetty & Baik 2006; Gomez et al. 2001; Niño-Medina et al. 2019) therefore it is more interesting to look at hardness over time which will be discussed further in section 4.3.2 – Moisture content over time.

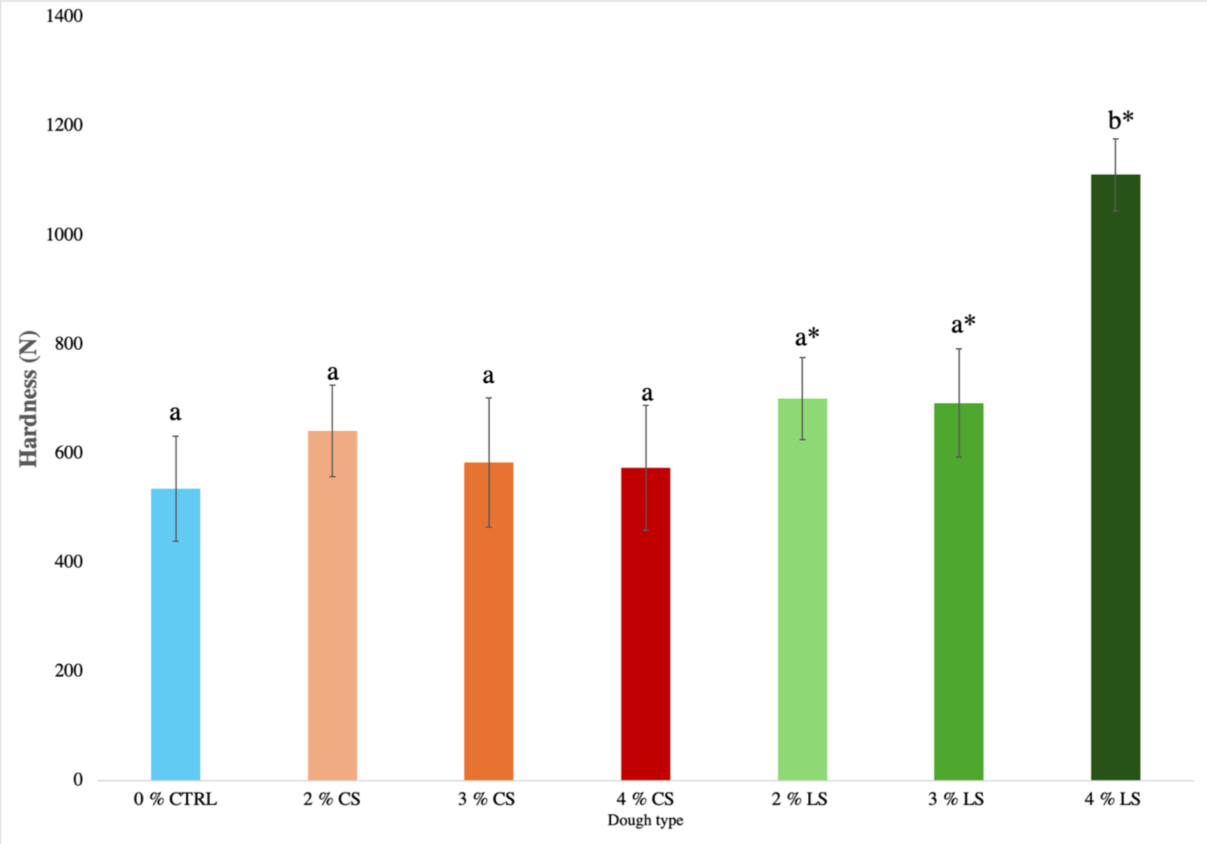

*Figure 7. Average hardness of breads in experimental design. Each dough type is baked in duplicates and breads analyzed in triplicates, a total of six measurements per dough type. Different letters indicate a signifiant difference with 95 % confidence. * indicates significant difference compared to CTRL with Dunettes comparison to CTRL with 95 % confidence. CTRL = control bread with no added fiber, CS = fiber derived from the hull, LS = fiber derived from cotyledon.*

Table 8. Cohesiveness and springiness measured on day 1. Different letters indicate a significant difference with 95 % confidence.

	Cohesiveness	Springiness
CTRL	0.72 bc	0.95 b
2 % CS	0.70 a	0.95 ab
3 % CS	0.72 abc	0.93 a
4 % CS	0.71 ab	0.95 b
2 % LS	0.73 cd	0.95 b
3 % LS	0.75 d	0.96 b
4 % LS	0.73 bcd	0.95 ab

4.3. Shelf-life bread results and discussion

Shelf-life doughs were baked in upscaled recipes and made with a stand mixer to obtain larger quantities of breads. Bread was stored in resealable plastic bags at room temperature and specific volume, texture profile analysis, and moisture content were measured on day 1, day 7, and day 14. For the consumer study, bread was frozen on day 1 and thawed the night before the consumer test.

4.3.1. Specific volume

LS has significantly lower specific volume compared to CS and CTRL at 2 % fiber addition, further confirming that incorporating LS side stream in bread decreases the specific volume of bread (Table 9).

As discussed above, this could be due to LS having higher WHC and thus, gluten structure being impaired due to competition for water (Zhou et al. 2017; Cauvain 2020). However, there was no significant difference in crumb structure confirming that, in the crumb structure by image analysis as shown in Table 6 in section 4.2.4.

Table 9. Average specific volume of breads from shelf-life and sensory analysis. Different letters in the same column indicate a significant difference and 95 % confidence.

	Specific volume (ml/g)		
Dough type	**Day 1**	**Day 7**	**Day 14**
CTRL	3,7 ab	3,6 ab	3,7 a
2 % CS	3,5 b	3,6 ab	3,6 ab
2 % LS	3,2 c	3,2 c	3,2 c

4.3.2. Moisture content over time

All samples lost moisture over time from day 1 to day 14 as expected due to evaporation. LS had significantly (statistics, Table V, Appendix V) higher moisture content in all parts of the bread (top crust, middle crumb and bottom crust) on days 1 and 7, including the crumb on day 14. CS and CTRL had similar moisture content throughout the shelf-life study. This suggests LS not only has higher WHC as shown in Table 3 yet also retained this water over time. As previously discussed, moisture retention over time could delay bread staling (Young 2012; Dalgetty et al. 2006; Niño-Medina 2019; Klava et al. 2000).

During storage of bread the water moves from the gluten to starch as well as from the crumb to the crust (Young 2012). The redistribution from crumb to crust might be seen in figure 8 in CTRL bread. Moisture content in both top and bottom crust increase while crumb moisture content seemingly continues to decrease. This is, however, not as clearly seen with CS and LS. Perhaps the moisture has yet to redistribute in these breads or is bound more tightly to LS and CS side streams, especially considering LS retained significantly (Table V, Appendix V) higher crumb moisture content even on day 14 of the shelf-life study.

Dalgetty & Baik (2006) showed that both pea hull and insoluble cotyledon fibers increased the moisture content of bread and retained moisture over time (Dalgetty & Baik 2006) which aligned with the results of LS (derived from cotyledon) but not however with CS (derived from hull). The reason as to why CS did not retain higher moisture compared to CS might be explained by other reasons such as processing and starch properties of the side stream.

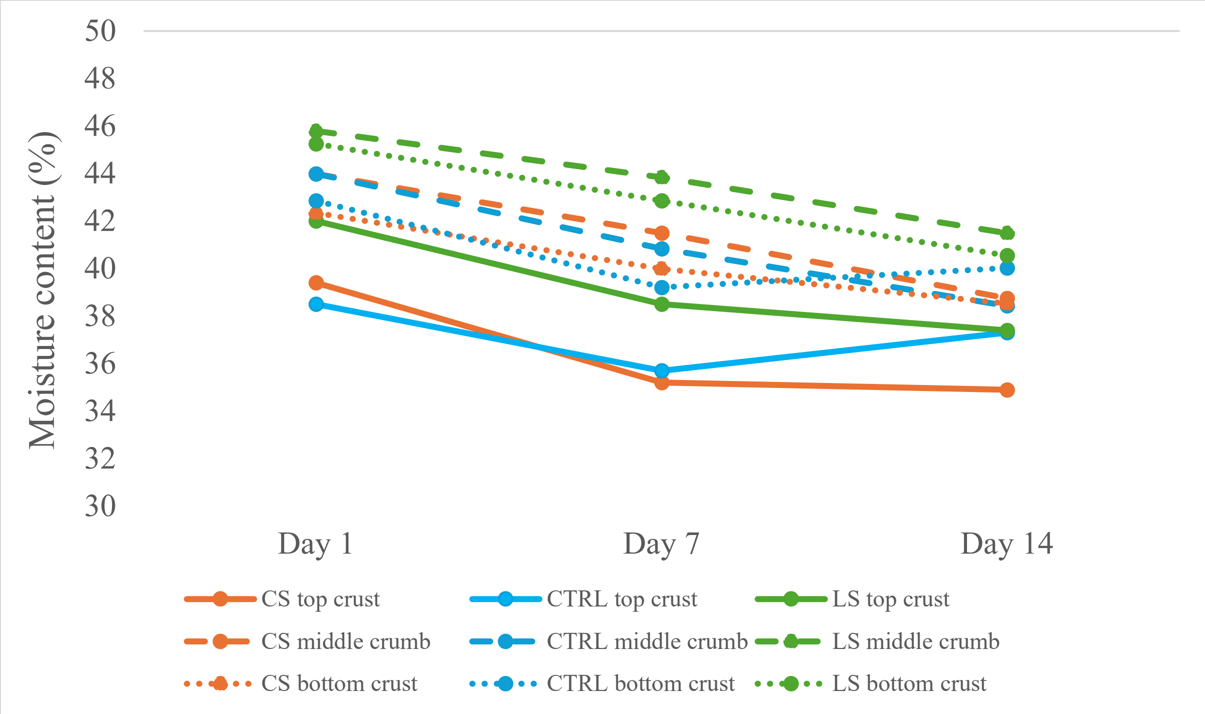

Figure 8. Moisture content (%) in crust and crumb over time in breads baked for cosnumer test. A total of six breads analyzed for each dough type on day 1, 7, and 14 after baking. The y-axis is truncated (30–50%) to enhance the visibility of differences between samples.

4.3.3. Texture profile analysis over time

Change in hardness

Multiple studies have shown that the fortification of pea fiber can delay crumb hardness over time due to moisture retention over time delaying starch retrogradation (Dalgetty & Baik 2006; Gomez et al. 2019; Niño-Medina et al. 2021).

As LS fortification retained higher moisture content in bread on day 1 and 7 it could be expected that the change in hardness would also be delayed in these breads. This was not the case as all the different bread types all had similar change in hardness as seen in figure 9. In terms of fortifying bread with side streams to support a "source of fiber" claim, this is a promising result, as neither type of side stream caused a significant difference in hardness change over time compared to the control.

It is important to notice that even if Figure 9 suggests that the staling rate of the breads are not affected by side stream fortification, the actual hardness of the crumb of LS was significantly harder on day 1 and day 7 compared to CTRL and CS. The statistical difference in hardness is shown in Figure II in appendix V . As previously discussed in the original experimental design, the increased hardness of LS might be due to a denser crumb structure which in turn may be due to increased WHC interfering with the gluten formation (Dalgetty et al. 2006) even though this was not statistically confirmed by the results of the crumb structure by image analysis. It is also important to note that staling of bread is impacted by starch retrogradation and the recrystallization of amylopectin in bread (Young 2012). As the side streams contain 60 % starch it is interesting to look further into the specific technological properties of the starches in the side streams and what role they could be playing in bread staling.

To conclude, even though the staling rate, i.e. the change of hardness was similar across the breads, LS was significantly harder compared to CTRL and CS which is an important parameter for the consumer when considering the choice of bread. Consumers' acceptance of the fortified breads is further discussed in section 4.3.4 – Sensory evaluation.

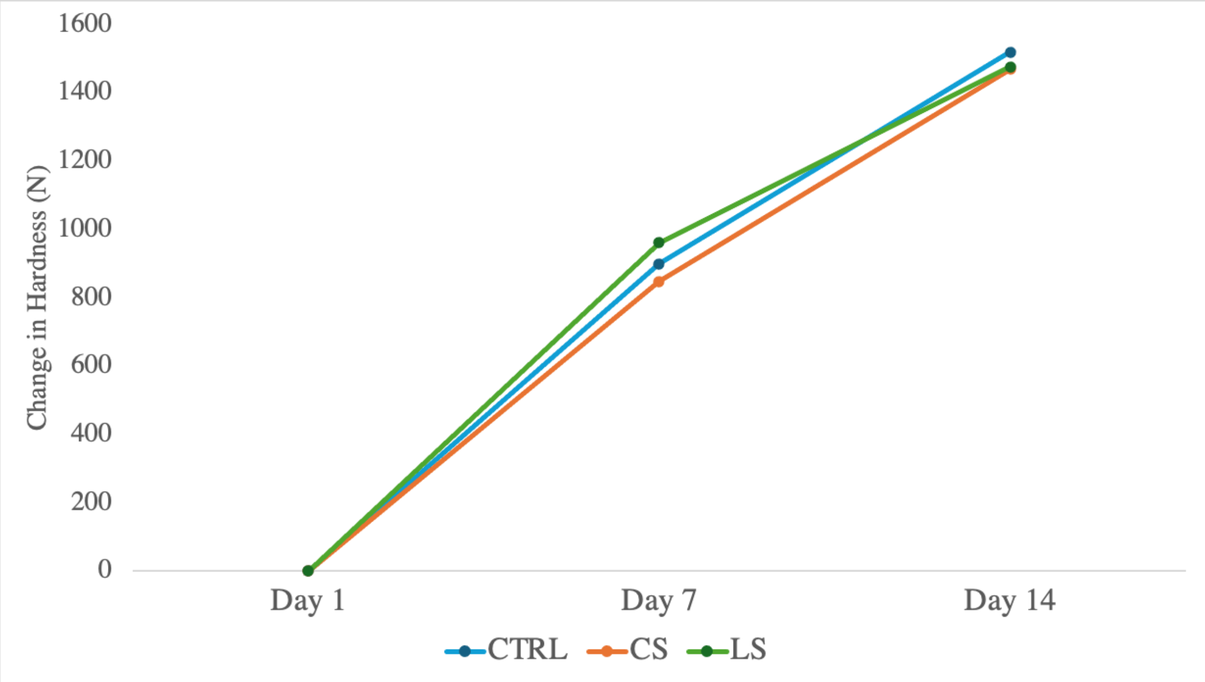

Figure 9. Change in hardness over time, measured on day 1, day 7 and day 14 of shelf-life breads (CTRL = without fiber, LS = derived from cotyledon, CS = derived from hull).

Cohesiveness and Springiness

Cohesiveness decreases over the 14-day period from approximately 0.7 to 0.45. As did springiness, though not as distinguishable as for cohesiveness (Table 10). LS has higher cohesiveness on all measured days which could suggest that fortifying bread with LS could be positive for bread storage as is usually a desired trait which is affected both by moisture content and the strength of the crumb structure (Young 2012). However, addition of LS was only a significantly higher on day 7 so it was concluded that side streams generally had no effect on cohesiveness.

There were no significant differences between the breads regarding springiness. As mentioned above, springiness refers to how well the crumb of the bread bounces back to its original shape after being pressed. This tends to decrease as the bread stales (Young 2012) and as there were no significant changes in springiness this would imply that incorporating side streams do not show any differences in springiness compared to white bread (CTRL).

Table 10. Cohesiveness and springiness measured on day 1, day 7, and day 14 after baking. Different letters within the same column imply significant difference with 95 % confidence.

	Cohesiveness			Springiness		
Dough type	**Day 1**	**Day 7**	**Day 14**	**Day 1**	**Day 7**	**Day 14**
CTRL	0.72 a	0.49 b	0.45 a	0.96 a	0.91 a	0.91 a
CS	0.72 a	0.48 b	0.44 a	0.95 a	0.90 a	0.91 a
LS	0.74 a	0.54 a*	0.46 a	0.96 a	0.91 a	0.92 a

4.3.4. Sensory analysis

A total of 88 responses were collected at the Campus of SLU. 65 % of the respondents were women and 35 % were men and the majority (70 %) of the respondents were between 18-34 years old. Over 80 % of the respondents ate bread at least once a week and 65 % ate bread daily or a few times a week.

There was a high standard deviation (Table 11), indicating that the responses varied widely in scoring. Table 11 shows the average score on the hedonic scale from (1) "Like extremely" to (9) "Dislike extremely". The scores of each bread sample (CTRL, LS, CS), ranked 3 or closer to 4 or the equivalent to "Like moderately" to "Like slightly". A total of 88 answers were collected with each individual scores on texture and taste. There were no significant differences between the sample scoring on texture or taste (Table VIII, Appendix VI).

Table 11. Average scores and standard deviations on the hedonic scale from (1) "Like extremely" to (9) "Dislike extremely".

Sample	Texture average	Taste average
CTRL	3.2±1.6	3.1±1.2
2 % LS	3.3±1.5	3.4±1.5
2 % CS	3.2±1.4	3.5±1.5

To further investigate, the respondents were divided into two groups depending on the consumption habits of soft bread. *High:* from eating soft bread every day to a few times a week, and *Low*: from once a week to never. High consumption group was made up of 57 respondents and low consumption group was made up of 31 respondents. The two groups showed no significant differences in scoring the individual bread samples except in the texture of 2 % CS (Table X, Appendix VI). The average score on the hedonic scale ranges from (1) "Like extremely" to (9) "Dislike extremely". The group of higher bread consumption gave a subsequentially higher liking score of 2.9 compared to the group of lower consumption which gave the score of 3.6.

Preference

32 respondents preferred CTRL and 32 respondents preferred LS. Meanwhile CS was preferred, only by 24 respondents, however there was no statistical support in preference differences between the bread samples (Table IX, Appendix VI).

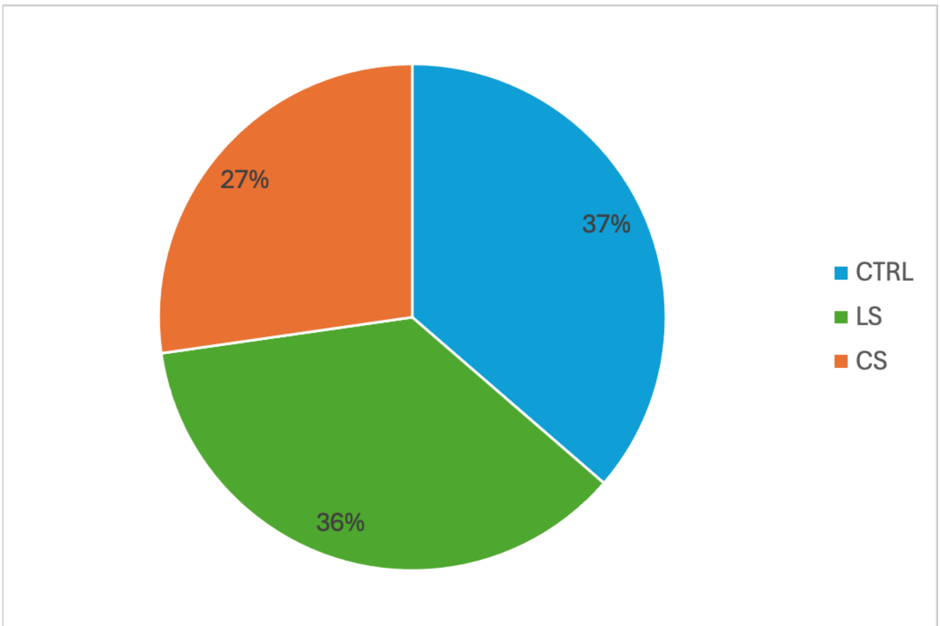

Figure 10. Preferred sample in consumer test.

However, there was a difference in preference while looking at the *Low* consumption group. Within the group that consumed bread once a week or less, only 4 respondents preferred CS bread. The same group scored statistically different in the liking of the texture compared to the high consumption group. This could suggest that low frequency bread consumers are less inclined to like bread fortified with CS. Generally, there was still an acceptance for LS.

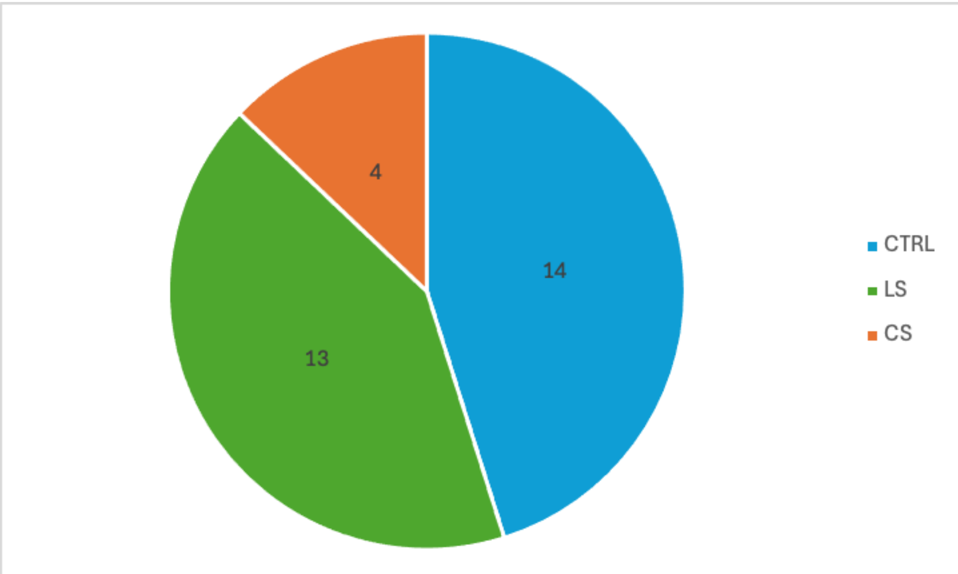

Figure 11. Preferred sample by the low frequency consumer group.

The comments from the respondents were varied in describing the texture and the taste of the breads. Words like neutral, normal, plain, flavorless and bland were described across all three samples. Both soft and fluffy mixed with dry and moist also were described making it difficult to interpret any sort of conclusive wording describing the different breads. This corresponds to the no significant difference of preference between the breads or the scoring of neither the taste nor texture of the bread samples. However, among the neutral describing words, sourness was a word that was mentioned a few times describing the taste of both LS and CS.

The consumer test was performed in a public location which calls for approximately 100 + respondents for credible results (Stone et al. 2021), however the final number of completed surveys was slightly below that of 88 responses.

There are advantages and disadvantages of carrying out a consumer test in a public location: this experiment allowed for many participants and practical sample distribution, using plastic bags, and QR codes made the survey easy to access. However, the disadvantage with a public location was not having full control as in a laboratory environment (Stone et al. 2021; Gustafsson et al. 2019). Using six different QR-codes ensured the possibility of a balanced serving order for higher reliability (Stone et al. 2021).

Despite significantly harder crumb in LS on day 1 and 7 of the shelf-life breads, the difference was not detected, by liking, by the general group of consumers. This indicated that the instrument (TPA) might be more sensitive than human perception in this aspect. The fact that no bread sample was preferred over the others by the general respondents would suggest that fortifying bread with 2% LS side stream into white bread could be accepted from a consumer standpoint. It is however important to take into consideration only small cut out crumb pieces were served, and entire bread loaves were not evaluated and even at 2 % LS had visually lower specific volume than CS and CTRL. An analytical sensory test with a trained panel is suggested for a closer evaluation of the breads and to further investigate the sourness mentioned by a few.

Generally, there were no significant changes in crust color when breads were fortified with either of the side streams. This differs from previous studies where pea fiber fortification has affected both crust and crumb color. In this study, a small increase in crumb redness was seen with LS, however this was not visible to the naked eye. This suggests that the incorporation of pea protein side streams could be promising in terms of maintaining the typical appearance of white bread.

Textural properties, cohesiveness and springiness also showed no significant differences between the fortified samples and the control bread. Although crumb structure measured through image analysis suggested a potential decrease, this trend was not statistically supported. All together, these results indicate that multiple key baking quality parameters were not negatively impacted by the addition of side streams at the tested levels.

However, LS fortification resulted in a significant decrease in specific volume, which aligns with previous studies reporting volume loss as a common challenge when adding fiber to bread. One likely explanation is the high water-holding capacity (WHC) of the cotyledon-derived LS fiber, which may compete with gluten proteins for available water during dough development, impairing gas retention. In this study, a non-significant decrease in cell count was also observed in image analysis, which could support the theory that reduced volume was partly caused by coalescence of gas bubbles, resulting in fewer, larger cells and ultimately a denser crumb structure. This denser crumb could also help explain the increased hardness observed in LS bread during the shelf-life study. However, as image analysis was only performed on fresh bread, this connection should be interpreted with caution. Moisture content increased in bread fortified with LS and was significantly retained over seven days of storage. While higher moisture levels are often associated with delayed staling, this effect was not seen here, as both side streams showed similar hardening rates over time compared to CTRL. In terms of texture, no major differences in firmness were seen in the fresh bread study, but in the shelf-life analysis, LS bread had a significantly firmer crumb on both day 1 and day 7.

Despite the firmer crumb in shelf-life breads with LS, the consumer test did not show any significant differences in preference or liking of taste and texture between the samples. Most comments described the breads using neutral terms such as “normal,” “neutral,” or “bland.” However, a few participants noted a slight sourness in both fortified breads. It was also suggested that low frequency consumers of soft bread were less inclined to prefer CS over CTRL and LS. This suggests that the tested level of fortification generally did not negatively affect consumer acceptability however future studies should involve analytical testing to evaluate the bread closer and look at the entire loaf and investigate taste nuances. It would further be interesting to test higher fiber levels to see whether the nutritional claim “high in fiber” could be met without affecting consumer acceptability.

To further investigate the potential of LS in bread, more detailed analysis of its fiber composition and physical structure is needed. Enzymatic treatment has shown promise in previous studies for modifying fiber properties to improve loaf volume and dough performance (Jiménez & Martínez-Anaya* 2001; Pietiäinen 2024). Other strategies like pre-soaking fibers or combining LS with other functional ingredients could also be explored.

Lastly, it is important to consider the role of starch in the side streams. The side streams contain approximately 60% starch, which not only interacts with water but also affects shelf life through starch retrogradation. Starch likely contributed to both the textural properties and moisture behavior observed in this study, and its interaction with fiber is an important area for further research when developing functional breads from side streams.

5. Conclusion

Fortification of bread with LS significantly affected multiple baking properties. LS reduced specific volume, increased moisture content in all parts of the bread and retained moisture over time. There was no difference in hardening over time between the breads and fortification of bread with side streams initially indicated no difference in texture however, LS fortification resulted in firmer crumb over time compared to CS and CTRL. Despite significant textural differences in shelf-life bread, consumers showed a general acceptability for fortified breads which implies that incorporating low levels of LS at levels to support the nutrition claim "source of fiber" under EU regulation in white bread is a possibility. Further studies should explore processing methods to improve baking performance and evaluate whether higher fiber levels can be used while maintaining quality. By doing so, nutritional value can be added while also contributing to reduced food loss, thus adding value to side streams and creating *sustainable slices*.

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Popular Science Summary

Plant-based proteins are playing an increasingly important role in the shift toward more sustainable food systems. In Sweden, new dietary guidelines encourage higher legume consumption and reduced meat intake, both to promote health and to strengthen national food security. Efforts are being made in Sweden in increase pea protein production and with protein extraction comes by-products or side streams rich in fiber and starch.

These side streams often end up underused though they may hold great potential. One promising idea is to incorporate them into foods that are already widely consumed, such as white bread. Bread is a staple food and while it is widely consumed, white bread low in fiber is usually preferred. At the same time, only about one in three Swedes meet the recommended daily fiber intake. Fortifying white bread with side streams could therefore serve both nutritional and environmental goals, by increasing fiber intake and reducing food loss.

This study investigated the potential of using pea protein side streams in white bread, by comparing two side streams with a control white bread. A pilot side stream derived from the cotyledon part of the pea (LS), was developed by Lantmännen. The other side stream was a commercial blend made up of pea starch and fiber derived from the hull to represent the pilot side stream (CS). Both were added to white bread and compared to a control bread without any added fiber. The breads were evaluated for baking quality, shelf life, and consumer acceptability.

The results showed that the LS side stream significantly reduced bread volume, likely due to its high water-holding capacity which affects how the dough traps gas during fermentation. A lower gas cell count, though not statistically significant, supported the idea that gas bubbles coalesced and resulted in a denser crumb. LS bread also retained more moisture over time, but this did not delay the staling process compared to the control. The crumb became firmer during storage, especially in the LS bread, which could be linked to its denser structure.

Despite textural differences, the consumers did not show any strong preference for one bread over another. Comments were mostly neutral, and many described the breads as “normal” or “bland.” A few mentioned a slight sourness in the fortified breads, and some variation in preferences was observed among people who ate soft bread less frequently. In general there was an overall acceptability for the fortified breads, including for the LS bread.

These findings suggest that it is possible to incorporate small amounts of pea protein side streams into white bread without compromising consumer acceptance, while improving the nutritional value enough to meet the EU definition of a “source of fiber.” Further research could focus on improving the baking performance of LS, and testing whether higher fiber levels can be used without affecting quality. With smarter use of side streams, bread could contribute to a more resource-efficient and health-promoting food system – creating *Sustainable Slices.*

Appendix I – Assessment prior to experimental design

Table I shows baking absorption and DDT. Baking absorption is in this case the ratio of water to flour to obtain 480 BU in this case. DDT was estimated by looking at farinograms to obtain dough consistency of 480 BU.

Table I. Dough results showing amounts of water added and dough consistency.

Code	Dough type	Added water	BU
D6	0 % CTRL	197.0	450
D16	0 % CTRL	197.0	480
D13	2 % CS	197.0	490
D17	2 % CS	197.0	560
D5	3 % CS	199.0	480
D14	3 % CS	199.0	480
D8	4 % CS	201.0	460
D18	4 % CS	215.0	560
D11	2 % LS	215.0	500
D15	2 % LS	215.0	510
D7	3 % LS	235.0	460
D10	3 % LS	235.0	460
D9	4 % LS	255.0	410
D12	4 % LS	245.0	460

Appendix II – recipes for experimental design.

Table II. Recipes used for fresh breads in experimental design. These recipes were scaled up for shelf-life study and consumer test.

CTRL

	bakers %	amount (g)
mjöl		283.7
LS		0.0
GP		0.0
olja	0.025	7.1
socker	0.05	14.2
salt	0.015	4.3
jäst	0.046	3.7
sorbic acid	0.0015	0.4
vatten		197

2 % CS

	bakers %	amount (g)
Fibradan		5.6
Cosucra		8.6
GP		2.2
Oil	0.025	7.1
Sugar	0.05	14.2
Salt	0.015	4.3
Yeast	0.046	13.1
Sorbic acid	0.0015	0.4
Water		197

2 % LS

	bakers %	amount (g)
Flour		267.3
LS		13.9
GP		2.2
Oil	0.025	7.1
Sugar	0.05	14.2
Salt	0.015	4.3
Yeast	0.046	3.7
Sorbic acid	0.0015	0.4
Water		215

3 % CS

	bakers %	amount (g)
Flour		259.1
Fibradan		8.4
Cosucra		13.0
GP		3.3
Oil	0.025	7.1
Sugar	0.05	14.2
Salt	0.015	4.3
Yeast	0.046	13.1
Sorbic acid	0.0015	0.4

3 % LS

	bakers %	mängd (g)
Flour		259.1
LS		20.9
GP		3.3
Oil	0.025	7.1
Sugar	0.05	14.2
Salt	0.015	4.3
Yeast	0.046	3.7
Sorbic acid	0.0015	0.4
Water		

Water	199

4 % CS		
	bakers %	amount (g)
Flour		250.9
Fibradan		11.2
Cosucra		17.3
GP		4.5
Oil	0.025	7.1
Sugar	0.05	14.2
Salt	0.015	4.3
Yeast	0.046	13.1
Sorbic acid	0.0015	0.4
Water		

4 % LS		
	bakers %	amount (g)
Flour		250.9
LS		27.8
GP		4.4
Oil	0.025	7.1
Sugar	0.05	14.2
Salt	0.015	4.3
Yeast	0.046	3.7
Sorbic acid	0.0015	0.4
Water		245

Appendix III - Starch analysis

Table III. Average resistant starch (RS) and digestable starch (DigS) and standard deviations of raw ingredients.

Flour/fiber	RS (g / 100g)	DigS
Wheat flour	2.4 ± 0.3	63.2 ± 6.1
LS (cotyledon side stream)	1.0 ± 0.0	38.4 ± 0.7
NASTAR Cosucra native pea starch	50.2 ± 5.3	45.8 ± 4.0
Vestkorn Fibradan F20X	0.0 ± 0.0	0.7 ± 0.1
Gluten powder	4.7 ± 0.6	5.8 ± 2.2

Appendix IV – Fresh bread

*Table IV. Average results of all parameters measured on breads in experimental design, measured on day 1. Different letters in the same row indicate significant differences at p<0.05. Dunnette pairwise comparison to control bread is indicated with *. CTRL = bread without added fiber, CS = fiber derived from hull, LS = fiber derived from cotyledon.*

	CTRL	2 % CS	3 % CS	4 % CS	2 % LS	3 % LS	4 % LS
Specvol	3.9 c	3.8 c	3.9 c*	3.8 c	3.2 b*	3.1 b*	2.7 a*
Hardness	534.8 a	641.4 a	583.4 a	573.5 a	700.6 a*	692.1 a*	1110.8 b*
Cohesiveness	0.72 bc	0.70 a*	0.72 abc	0.71 ab	0.73 cd	0.75 d*	0.73 bcd
Springiness	0.95 b	0.95 ab	0.93 a	0.95 b	0.95 b	0.96 b	0.95 ab
MoistureT	0.370 a	0.372 a	0.375 ab	0.369 a	0.4 b*	0.439 c*	0.449 c*
MoistureM	0.433 ab	0.43 a	0.428 a	0.432 ab	0.452 bc*	0.464 c*	0.494 d*
MoistureB	0.413 a	0.41 a	0.409 a	0.422 ab	0.441 b*	0.47 c*	0.482 c*
Cell count	1937.7 a	1788.0 ab	2080.0 a	1671.3 ab	1591.0 b	1698.0 ab	1917.3 ab
Avgsize	123.3 a	118.4 a	116.3 a	124.4 a	182.0 a	132.8 a	124.5 a
Areaperc	26.6 a	23.5 a	27.1 a	23.0 a	28.8 a	24.8 a	26.4 a
L*crust	41.6 a	43.8 a	43.3 a	41.2 a	44.0 a	44.2 a	45.3 a
L*crumb	69.3 a	70.1 a	69.7 a	63.6 a *	70.2 a	68.9 a	70.2 a
a*crust	8.7 a	9.3 a	9.0 a	8.0 a	9.2 a	9.0 a	9.4 a
a*crumb	-9.5 d	-9.1 c*	-9.1 c*	-9.1 c*	-9.0 bc*	-8.7 ab*	-8.6 a*
b*crust	32.1 a	34.2 a	33.2 a	32.1 a	34.2 a	32.9 a	35.5 a
b*crumb	35.8 bc	36.7 ab*	36.4 ab	35.2 c	36.8 a*	36.4 ab	37.2 a*

Figure I. Scanned images of all bread slices of fresh breads.

Appendix V – Shelf-life bread

Table V. Average moisture content in different parts of the bread (T=top crust, M=middle crumb, B=bottom crust) measured on day 1, day 7 and day 14. Different letters in the same row indicate significant differences at p<0.05. CTRL = bread without added fiber, CS = fiber derived from hull, LS = fiber derived from cotyledon.

	MoistureT (%)			MoistureM (%)			MoistureB (%)		
Dough type	**Day 1**	**Day 7**	**Day 14**	**Day 1**	**Day 7**	**Day 14**	**Day 1**	**Day 7**	**Day 14**
CTRL	38.5 b	35.7 b	37.3 a	44.0 b	40.9 b	38.5 b	42.9 b	39.2 b	40.0 a
CS	39.4 b	35.2 b	34.9 a	44.0 b	41.5 b	38.8 b	42.4 b	40.0 b	38.5 a
LS	42.0 a	38.5 a	37.4 a	45.8 a	43.9 a	41.5 a	45.2 a	42.9 a	40.5 a

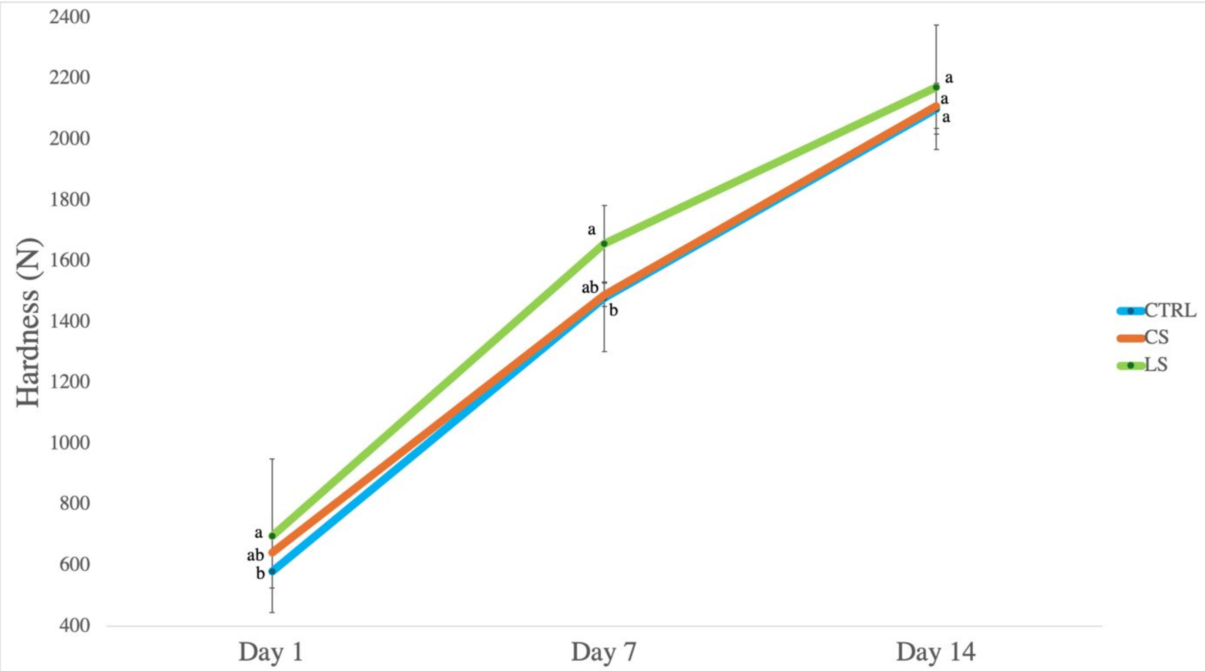

Figure II. Hardness over time, measured on day 1, day 7 and day 14 of shelf-life breads (CTRL = without fiber, LS = derived from cotyledon, CS = derived from hull). Different letters indicate significant difference with 95 % confidence.

Appendix VI – sensory evaluation

Table VI. Three-digit codes used in consumer test.

Sample	Code	Bread type
A	246	CTRL
B	523	2 % LS
C	480	2 % CS

Table VII. Summary of statistical analysis of evaluated sensory parameters.

Parameter	Test type	Chi-square value (X^2)	Degree of freedome (df)	p-value
Texture	Friedman Test	1.6	2	0.450
Taste	Friedman Test	3.65	2	0.161

A Chi-square test was performed to test if any of the samples, CTRL, LS, CS were significantly preferred. The Chi-square value was calculated to 1,45 and was compared to the critical value 5,99 for p<0,05 as seen in table VIII below. The Chi-square value 1,45<5,991 meaning the null hypothesis could not be rejected and therefore there was no significant preference between the bread samples, among the consumers.

Table VIII. Critical value for signifcance and degree of freedom (Gustafsson et al. 2014).

		Significance	
df	**0.05**	**0.01**	**0.001**
1	3.84	6.64	10.83
2	5.99	9.21	13.82
3	7.82	11.34	16.27
4	9.49	13.28	18.46
5	11.07	15.09	20.52

Table IX. Summary of Chi-square test for statistical analysis of preference between the bread samples, A, B, C.

Sample	Preferred	Expected	$[\Delta]^2$/Expected
CTRL	32	29,33	0.24
2 % LS	32	29,33	0.24
2 % CS	24	29,33	0.97
Sum:			**1.45**

Table X. Table over average sample scoring and standard deviation in groups of high bread consumption (From eating bread every day to a few times a week) and low bread consumption (from once a week to never).95 % confidence level.

Sample	Attribute	Consumption group	Mean ± SD	p-value
CTRL	Texture	High	3.1 ± 1.3	
CTRL	Texture	Low	3.5 ± 2.0	0.320
CTRL	Taste	High	3.1 ± 1.1	
CTRL	Taste	Low	3.2 ± 1.4	0.800

2 % LS	Texture	High	3.3 ± 1.4	
2 % LS	Texture	Low	3.2 ± 1.8	0.640
2 % LS	Taste	High	3.5 ± 1.5	
2 % LS	Taste	Low	3.2 ± 1.7	0.400
2 %CS	**Texture**	**High**	**2.9 ± 1.2**	
2 % CS	**Texture**	**Low**	**3.6 ± 1.8**	**0.04**
2 % CS	Taste	High	3.3 ± 1.8	
2 % CS	Taste	Low	3.9 ± 1.8	0.100

Table XI. Survey questions with example sample A. Questions were replicated for B and C in randome order for each survey.

Question	Answer options
Welcome to this bread study! This study is part of my master's thesis and is included in the project 'Ending food waste from plant to plate,' in collaboration with Lantmännen. The study aims to examine the taste and sensory properties of bread. Please read the instructions carefully before proceeding with the test. Your participation is entirely voluntary, and you can withdraw at any time without providing any explanation. In order to participate in this test, you must also consent to having your responses used in this study. Participation is anonymous, and the results cannot be linked to any individual. When you are ready, click NEXT to proceed to the test. You will be asked to assess three samples in total. Take one sample at a time. The following allergens may be present in the test samples: Gluten, pea, sorbic acid. By clicking "I agree" below, you consent to having your responses used within the scope of this project and confirm that you have received sufficient information to participate. I consent to participate in this study.	Yes / NO
Sample A	
Drink water. Try sample A, focus on its taste and texture as you try it. Test sample A. How do you perceive the texture of sample A?	Like extremely Like very much Like moderately Like slightly Neither like nor dislike Dislike slightly Dislike moderately Dislike very much Dislike extremely

Describe what influenced your experience of the texture of sample A.	*Textbox*
Try sample A. How do you perceive the taste of sample A?	Like extremely Like very much Like moderately Like slightly Neither like nor dislike Dislike slightly Dislike moderately Dislike very much Dislike extremely
Describe what influenced your experience of the texture of sample A.	*Textbox*
What is your overall experience of sample A?*	Like extremely Like very much Like moderately Like slightly Neither like nor dislike Dislike slightly Dislike moderately Dislike very much Dislike extremely
Describe what influenced your overall experience of sample A.*	*Textbox*
Other comments about sample A.	*Textbox*
Preferens	
Of the samples you have just tried. Which sample do you prefer?	A B C
Bread habits/information about respondent	
How old are you?	18-24 25-34 35-44 45-54 55-64 65+
Gender	Woman Man Other/prefer not to say.
How often do you eat soft bread?	Every day. A few times a week. Once a week.

	Once a month. Less often. Never. I don’t eat soft bread.
Thank you	
Thank you very much for your participation! Reuse the plastic bag or recycle it at an appropriate location.	

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While baking one of the bread batches, someone passing by said *"It reminds me of my hometown"*. That simple comment stayed with me, and I think it captured what bread means to so many people around the world. Bread is more than just food; it's comfort, memory, and a sense of belonging. It's a staple food that connects cultures, generations, and daily life. And finally, a warm thank you to Leonor, who took part in my extra special sensory evaluation, your joy and enthusiasm brought me great happiness.