Plant-based products as a more sustainable source of protein: Exploring physico-chemical and sensory properties and consumer response

DOCTORAL THESIS
Submitted for the degree of Doctor by:

Djemaa Moussaoui
Master in Food Safety and Quality Assurance

Madrid, 2024
Doctoral Degree in Agro-environmental Technology for
Sustainable Agriculture

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Dr. Amparo Tarrega

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Thesis Defense Committee:

Thesis Defense Date:

This thesis has been partially supported by the Algerian government through the Pre-Doctoral scholarship offered to Djemaa Moussaoui. Additionally, funding for this thesis has been provided by MCIN/AEI/10.13039/501100011033 through financial assistance to the project PID2019 107723RB-C21, and by the Spanish government through MCIN/AEI for the Center of Excellence Accreditation Severo Ochoa (CEX2021-001189-S/MCIN/AEI/10.13039/501100011033).
Acknowledgements

First and foremost, I am profoundly thankful to the Algerian government for offering the scholarship that made my doctoral studies possible. This opportunity has been transformative, allowing me to pursue my academic and research aspirations. I am truly honored to have been a beneficiary of this opportunity.

Of course, this could not begin any other way than by thanking my thesis supervisors: Dr. Carolina Chaya and Dr. Amparo Tárrega for their patience, for their unconditional support in the most difficult moments and their invaluable mentorship. Their expertise, dedication, and insightful feedback has played a crucial role in guiding the direction of this research. In brief, I extend my gratitude to both of you for your exceptional kindness and professionalism.

I would also like to thank the SENSUPM team, Jordi, Gabriel, and to all the scholarship students Ramon, Sergio, Isabel, Paula, Javier, Claudia, Miguel. I have learned so much from each of you and I enjoyed sharing time and work with you.

I would also like to thank all the people of Institute of Agrochemistry and Food Technology (IATA-CSIC) of Valencia–Spain that I had the great opportunity to meet through my stay. Special thanks to the girls of Sensiata Lab (Celia, Patricia, Maria, Moni, Arantxa, Eli, Raquel and Laura) who have accompanied me from the beginning and who generously shared their time, insights, and experiences and were always available.

I owe a debt of special gratitude to my parents for their unwavering support, understanding, and encouragement. Their sacrifices, both big and small, have been the foundation upon which my educational pursuits have been built. I am also deeply thankful to my dear sister Souad, my brothers Lazhar, Miloud, El djemai, and Mohamed for their unwavering support and encouragement.

To my second family, Dezaeir, Djamila, Abla, Saliha and Wassim, for considering me as a daughter and sister, for welcoming me from the beginning with open arms and making me feel like one of the family.

To my friends Yasmina and Somia, who have accompanied me throughout this journey, not as friends but as a family, I can't forget your support and the beautiful moments we shared together.

I would also like to thank the Arhoun family, Mohammed Ali, Sonia, Inés and Hakim, who were the first to welcome me in Spain, for their kindness and support.

Finally, I would extend my sincere appreciation to the person who complements me, Samir, thank you for your unconditional love, for accompanying me in this project and in all the others, for taking care of me and knowing how to encourage me. I am deeply grateful for your presence in my life.
Abstract

Recently, there has been a growing interest about the world transition to a more sustainable and healthy food consumption. In this context, a better understanding of the challenges involved in making effective this transition is required. This Thesis aims at contributing to: i) the knowledge about the physicochemical and sensory properties of plant-based ingredients and products relevant for the development of novel plant-based food and ii) the analysis of consumers’ response towards plant-based food products.

In a first stage, the effects of pH and calcium on the techno-functional properties of four pulse flours (chickpea, lentil, red lentil, and white bean) and the rheological properties of their pastes and gels were studied. Results showed that the four pulse flours (chickpea, lentil, red lentil and white bean) exhibited different techno-functional properties that also varied with the conditions of pH and ionic strength. All pulse flours were good emulsifiers. In addition, white bean flour provided the higher water holding capacity, while lentil and red lentil flours were good as foaming ingredients. Chickpea flour exhibited high thickening capacity while red lentil exhibited high gelation capacity. Lowering pH and adding calcium increased water holding, foaming and thickening capacities, while it decreased emulsifying and gelation capacities.

In a second stage, the effect of varying the concentration of four ingredients (flour, oil, lemon, and salt) on the mechanical and sensory properties of three pulse gels (lentil, red lentil, or chickpea) was investigated. Mechanical properties varied differently with the formulation depending on the pulse type. For all pulses, the hardness and stiffness increased with flour content and decreased with salt. The same properties decreased with lemon in chickpea gels and increased with oil content in red lentil gels. Regarding the sensory properties of pulse gels, the Flash Profile technique provided distinctive sensory characteristics of each pulse gel. The red lentil gels were homogeneous, creamy and compact. The chickpea gels were also compact, but harder. Lentil flour resulted in rough and sandy gels. For the three pulses, including oil and lemon reduced pulse flavors and increased sour taste.

After that, consumer response elicited by the image of a plant-based burger was analyzed according to the information about the source of plant-protein (soy, pea and seitan (wheat)) and to consumers’ attitude towards meat reduction. The source of plant-protein did not affect consumers' response, but attitude towards meat reduction had a significant impact. Supporters of meat reduction showed higher acceptance and perceived plant-based burgers as healthier,
less processed, and more sustainable, while rejecters showed lower acceptance, lower healthy and sustainable perception and higher processed perception. In addition, plant-based burgers evoked positive emotions in supporters of meat reduction. Meanwhile, the samples evoked negative emotions in rejecters of meat reduction. Finally, Structural Equations Modelling analysis has been applied to understand the effect of consumers’ attitudes and concerns on their response towards plant-based products.

This Thesis provides insights for a better understanding of challenges faced by the food industry in the development of new plant-based products.
Resumen

La concienciación sobre la transición mundial hacia un consumo de alimentos más sostenible y saludable ha aumentado en los últimos años. En este contexto, se requiere una mayor comprensión de los desafíos que supone hacer efectiva dicha transición. Esta Tesis tiene como objetivos contribuir a: i) el conocimiento sobre las propiedades fisicoquímicas y sensoriales de ingredientes y productos vegetales relevantes para el desarrollo de nuevos alimentos basados en plantas y ii) el análisis de la respuesta de los consumidores hacia alimentos basados en plantas.

En una primera fase, se estudiaron los efectos del pH y el calcio sobre las propiedades tecnofuncionales de cuatro harinas de legumbres (garbanzo, lenteja, lenteja roja y judía blanca) y las propiedades reológicas de sus pastas y geles. Los resultados mostraron que las cuatro harinas de legumbres presentaban diferentes propiedades tecnofuncionales que también variaban con las condiciones de pH y fuerza iónica. Todas las harinas de legumbres fueron buenos emulsionantes. Además, la harina de judía blanca mostró la mayor capacidad de retención de agua, mientras que las harinas de lenteja y lenteja roja eran buenas como ingredientes espumantes. La harina de garbanzo tuvo una alta capacidad de espesamiento y la harina de lenteja roja tuvo una alta capacidad de gelificación. La disminución del pH y la adición de calcio aumentaron las capacidades de retención de agua, espumante y espesamiento. Sin embargo, la capacidad emulsionante y la capacidad de gelificación disminuyeron con la disminución del pH y la adición de calcio.

En una segunda etapa, se investigó el efecto de la variación de la concentración de cuatro ingredientes (harina, aceite, limón y sal) en las propiedades mecánicas y sensoriales de tres geles de legumbres (lenteja, lenteja roja o garbanzo). Las propiedades mecánicas variaron de forma diferente con la formulación según el tipo de legumbre. En todas las legumbres, la dureza y la rigidez aumentaron con el contenido de harina y disminuyeron con la sal. Las mismas propiedades disminuyeron en los geles de garbanzo al añadir limón, y aumentaron en los geles de lenteja roja al aumentar el contenido de aceite. En cuanto a las propiedades sensoriales de los geles de legumbres, la técnica Flash Profile proporcionó las características distintivas de cada gel de legumbres. Los geles de lentejas rojas fueron homogéneos, cremosos y compactos. Los geles de garbanzo también fueron compactos, pero más duros. La harina de lenteja dio lugar a geles ásperos y arenosos. Para las tres legumbres, la inclusión de aceite y limón redujo los sabores de las legumbres y aumentó el sabor ácido.

Después, se analizó la respuesta del consumidor evocada por la imagen de una hamburguesa vegetal, en función de la información sobre la fuente de proteína vegetal (soja, guisante o seitan (trigo)) y de la actitud de los consumidores hacia la reducción del consumo de carne. La fuente de proteína vegetal no afectó a la respuesta de los consumidores, pero la actitud hacia la
reducción de carne tuvo un impacto significativo. Los más partidarios de la reducción de carne mostraron mayor aceptación y percibieron las hamburguesas vegetales como más saludables, menos procesadas y más sostenibles. Sin embargo, los que estaban en contra de dicha reducción mostraron una menor aceptación y percibieron las muestras como menos saludables, menos sostenibles y más procesadas. Además, las hamburguesas vegetales evocaron emociones positivas en los partidarios de la reducción de carne, mientras que en el grupo que rechazaba la reducción de carne, evocaron emociones negativas. Finalmente, se aplicó el Modelo de Ecuaciones Estructurales para investigar el efecto de la actitud y preocupaciones de los consumidores en sus respuestas a productos de origen vegetal.

Esta Tesis contribuye a una mejor comprensión de los desafíos a los que se enfrenta la industria alimentaria en el desarrollo de nuevos productos basados en plantas.
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1. Chapter 1. Introduction
1.1 Plant-based products: the shift towards healthy and sustainable food system

Recently, there has been a growing awareness about human and planetary health and animal welfare that is driving the world transition to sustainable and healthy food (Michel et al., 2021; Seo et al., 2023). Accordingly, changing the world system towards more sustainable production is really challenging under the expected rise in population to 9.7 billion individuals by 2050. In addition, predicted growth in population is estimated to project an increase in meat and dairy product consumption by 23% on 2050 (FAO, 2018). In this perspective, several key alternative pathways for achieving sustainable food and agriculture by 2050 were suggested (FAO, 2018). These pathways include encouraging sustainable consumption patterns that reduce food waste, promoting healthy diets and supporting sustainable production practices. A sustainable and healthy diet is defined by (WHO-FAO, 2019) as a diet that contributes to food security and healthy living with a lower environmental impact for the current and future generations.

Animal products like meat, egg and dairy provide essential nutrient such as high quality proteins, various minerals and vitamins. Furthermore, animal-based proteins play a crucial role in muscle growth and promoting balanced human health (Adesogan, 2022). In European countries, meat and animal products are considered as the main source of the dietary proteins. Furthermore, the supply of animal sources of proteins is increasing over the years (FAO, 2021). Nonetheless, it was reported that high meat consumption negatively affects human health and the environment, especially red and processed meat (McBey et al., 2019). Therefore, the increase in meat consumption may lead to an increase in diet-related diseases including non-communicable diseases, which basically concern high-income countries (Fehér et al., 2020). These diseases can range from nutrient deficiency and malnutrition to chronic health problems such as obesity, diabetes and cardiovascular disease. Non communicable diseases results from low intake of fruits, vegetables, legumes, whole grains, nuts and seeds, calcium and fibre; as well as high intake of red meat, processed meat, sugar-sweetened beverages, fatty acids, and sodium (Bryant, 2022). For instance, saturated fatty acids, which are frequently found in red and processed meat, can raise cholesterol levels and contribute to a number of health problems, including colorectal cancer, diabetes, hypertension, obesity, and cardiovascular disorders (Bryant, 2022; Fehér et al., 2020; McBey et al., 2019).

Intensive animal production derived by the increased demand of meat products is reported among the most unsustainable factors responsible for a variety of greenhouse gas emissions, land degradation and water supply and animal suffering as well (Espinosa-Marrón et al., 2022; Graça et al., 2015). Extensive ruminant livestock farming emits mainly methane, while
intensive livestock farming produces CO₂ and NO₂ mainly related to the production of feed for livestock (Eshel et al., 2019). Moreover, livestock agriculture exploits nearly 40% of the world's freshwater resources (Van Vliet et al., 2020; Vermeulen et al., 2012). Intensive animal production promote non-responsible practices regarding animal welfare as well as animal suffering and abuse. Therefore, it is highly recommended to reduce the large-scale production and consumption of animal-based products, which are considered as a source of protein (Biesbroek et al., 2023; Sabateánd & Soret, 2014). Accordingly, finding alternative sources of proteins for human consumption is highly required.

Switching the food system towards more plant-based diets to reduce global meat consumption and production could be a viable process for a healthy and more sustainable future (Fiorentini et al., 2020; Van Vliet et al., 2020). The term “plant-based” refers to products that are made only from plant components and do not contain ingredients from animal origin (Ostfeld, 2017). Plant products such as beans, peas, and nuts are also good sources of protein. Nevertheless, it is worth to note that, when compared to animal proteins, plant sources of proteins are often lacking in one or more essential amino acids. Furthermore, compared to animal proteins, plant sources of proteins are less gastro-intestinally accessible and digested (Rajpurohit & Li, 2023).

Plant-based diet is a dietary pattern that prioritizes eating food produced from plants and restricts or eliminates the consumption of most or all animal products (Gibbs & Cappuccio, 2022). Biesbroek et al., (2023) revised the health and environmental outcome of plant-based food consumption and production as compared to other food categories (Table 1). In general, the authors pointed out that plant-based products have a good nutritional benefits with low risk of diet related diseases as compared to other food categories (Biesbroek et al., 2023; De las Heras-Delgado et al., 2023). Additionally, it was reported that the shift towards a plant-based diet is not only beneficial to human health but also has the potential to reduce greenhouse gas emissions and to decrease the consumption of natural resources currently used for livestock production by 35-50% (Eshel et al., 2019; Gibbs & Cappuccio, 2022).

It was reported that many Western countries are projecting an increase in trend of flexitarianism, vegetarianism and veganism that is driving an interest in the consumption of products from plant origin (Dagevos & Verbeke, 2022). Most of these consumers opt to eliminate or decrease meat from their diet driven by ethical considerations and concerns for the welfare of farmed animals (Dagevos & Verbeke, 2022; Fanzo, 2015; Perez-Cueto et al., 2022). Nevertheless, despite recommendations for a shift towards more plant-based diets and the
increase of consumers reporting their willingness to reduce meat intake, European countries remain recording higher meat consumption over time (FAO, 2021a)

Table 1. Food categories as related to health and environmental impacts for usual dietary patterns and levels of consumption*

<table>
<thead>
<tr>
<th>Major food categories</th>
<th>Nutritional benefits</th>
<th>Risk of chronic disease &amp; mortality</th>
<th>Environmental impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant food (whole grains, fruits(^1), vegetables(^1), potatoes(^2), tubers(^2), legumes, nuts, and olive oil)</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Fish, seafood, and poultry</td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Dairy and eggs</td>
<td>High</td>
<td>Neutral to Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Red and processed meats</td>
<td>Moderate</td>
<td>Moderate to High</td>
<td>High</td>
</tr>
<tr>
<td>Sugar-sweetened beverages and refined grains</td>
<td>Low</td>
<td>Moderate to High</td>
<td>Low</td>
</tr>
</tbody>
</table>

* Order in the table based on nutrition, health, and environmental impact, not economy and culture.

**Notes**: Nutritional benefits are based on nutrient recommendations. Risk of chronic disease and mortality and environmental impact are based on per kilogram of food estimates according to (Clark et al., 2019).

\(^1\) Ranges in environmental impact depend markedly on production method (greenhouse or field grown) and functional unit.

\(^2\) When boiled or mashed, not if used as fried staple product. From (Biesbroek et al. 2023).

Generally, plant-based products in the market are designed to replace conventional animal-based products such as milk substitutes, meatless burgers, patties and egg replacers, or to mimic these products and their sensory properties such as flavor, texture and appearance (Espinosa-Marrón et al., 2022; Van Vliet et al., 2020). Mostly, the common sources of proteins used in plant-based food industry are soy and wheat (Michel et al., 2021). Soybeans are used to produce textured proteins, tofu, soymilk and tempeh. Wheat is usually used to produce seitan that is a meat substitute mostly included in the plant-based meat alternatives. Lately, pea proteins also have gained popularity for the production of various categories of plant-based products such as protein powders, plant-based burgers and dairy substitutes (Jeske et al., 2018). **Figure 1** shows the most common plant-based sources of protein and their potential uses as ingredients in different food and beverages categories.

In addition to protein sources, other ingredients such as coloring (cumin, lycopene, carotene, beetroot juice), flavorings (spices, herbs, paprika, sugar, salt), vitamins and other bioactive components are widely used in the plant-based food production. Oils (sunflower, coconut, palm, etc.) and other "structural" elements like carrageenan, starch, and cellulose are added to ensure that the texture and qualities are similar to those of imitated products such as meat products (Benković et al., 2023).
Figure 1. The most common plant-based sources of proteins and their potential use as ingredients in different food and beverages categories.

Although soy and wheat are widely used in food industry to produce plant-based products, the low diversity and dearth of satisfying textures and flavors of the existing plant-based products still primarily hinder consumers (Michel et al., 2021). Additionally, the prevalence of allergies to these ingredients is an additional concern that discourage many consumers from purchasing them. Furthermore, it should be considered that flexitarians, who aim to cut back on their use of animal products without eliminating them, are the primary force behind the anticipated rise in demand for plant-based products. Hence, when looking for plant-based products, these consumers may choose various product concepts or recipes that they may prefer and incorporate into their diet rather than "imitation" of their usual food concepts (Dagevos, 2021). Accordingly, it has been suggested that one way to improve the quality of alternative products and to convince a larger group of consumers is to use a wider variety of plant-based ingredients to develop nutritious and appealing food options with less environmental impact (Bravo-núñez & Gómez, 2021; Rajpurohit & Li, 2023; Shevkani et al., 2019).
1.2 The use of pulses in plant-based food products

Pulses belong to the *Fabaceae* family. The word "pulses" refers to grain legumes used primarily for human consumption or animal feed, and is derived from the Latin word "puls," which means puree, or broth. The Food and Agriculture Organization of the United States (FAO) defines pulses as the edible seeds of leguminous plants cultivated for both food and feed (FAO, 2016b). Various kinds of chickpeas (*Cicer arietinum* L.), lentils (*Lens culinaris* Medikus), beans (*Vigna angularis*), kidney beans (*Phaseolus vulgaris* L.), hyacinth beans (*Dolichos lablab* L. *Sweet*), broad beans (*Vicia faba* L.), lima beans (*Phaseolus lunatus* L.), Mung beans (*Vigna radiate* L.), black beans (*Vigna mungo* L *Hepper*) and vetch (*Vicia sativa* L.), cowpeas (*Vigna unguiculata* L.), peas (*Pisum sativum* L.), grass peas (*Lathyrus sativus* L.), pigeon peas (*Cajanus cajan* L. *Millsp*), edamame (*Phaseolus acutifolius* A. *Gray*), are commonly used in diverse conditions around the world, but beans (*Phaseolus and Vigna*), chickpeas, peas and lentils are the most common consumed types (Malcolmson & Han, 2019).

Pulses such as beans, chickpeas, lentils and peas exhibit high production volume worldwide, with average from 7 to 30 million metric tones per year, that varies significantly according to the pules category (Figure 2) (FAO, 2016a). Pulses production in Europe has an important share of the whole world, in particular in the Western part of the continent which has humid temperate climate. According to EUROSTAT 2020, total pulses production in European Union (EU) arrived to 4.110 thousand tones with the highest producers being France, Spain, Poland, Germany and Lithuania. Furthermore, if well stored, pulses remain edible for several years (long shelf life) and have a good impact on food security, health and environmental sustainability (FAO, 2016b). The year 2016 has been declared the International Year of Pulses by the FAO in order to raise the public awareness of the nutritional and sustainable benefits of pulses (Singh, 2017). Thereby, due to the high availability and production volume, their low costs and low allergenicity as compared to soy and wheat, pulses can offer a valuable alternative base ingredient for plant-based production (Bravo-núñez & Gómez, 2021).
From environmental standpoint, the incorporation of pulses in the cropping cycles contributes in reducing greenhouse gas emissions, land and water use for agricultural production (FAO, 2023). Carbon emission from pulses production are very low as compared to other food categories such as meat products. For instance, the production of 100 g of proteins from beef is estimated to emit 25 Kg of carbon dioxide equivalent (CO$_2$eq), while the production of the same amount of proteins from bean is only estimated to emit 0.65 kg of CO$_2$eq (Poore & Nemecek, 2018). Moreover, pulses require less water for their cultivation and can grow in a dry soil besides their tolerance to difficult environmental conditions. In addition, pulses can contribute in atmospheric nitrogen fixation, so they do not require nitrogen supply as fertilizer, meanwhile they release the extra-nitrogen on the soil, thus helping in the restoration of poor and deteriorated lands and enhancing their fertility (FAO, 2023).

Pulses are nutrient-dense providing an affordable source of complex carbohydrates, dietary fibers and proteins as well as several minerals and vitamins. They have almost 55-65% of carbohydrates (starches and fibers). Pulse starches are characterized by their low digestibility that contribute in their low Glycemic Index (GI) (Guillon & Champ, 2002). In addition, dietary fibers available in pulses can prevent diverse digestive disorders and contribute in satiety sensation that helps to weight managements (Proserpio et al., 2020). Moreover, given their high dietary fiber content which is known for reducing LDL cholesterol; pulses can help to reduce the risk of coronary heart disease (FAO, 2016a).

Pulses are gluten free and exhibit high protein content, as compared to cereals; they have almost the double of protein content, yet this content depend on the variety, degree of germination,
environment and the fertilizers used (FAO, 2016a). Protein content of pulses range from 20 to 30%, including essential amino acids such as lysine, leucine, aspartic acid, glutamic acid, and arginine, making them a valuable source of protein for human body (Shevkani et al., 2019). Nevertheless, they may be deficient in certain amino acids like methionine, tryptophan, and cysteine (Parveen et al., 2016). Table 2 presents the amino acid composition of some common pulses including essential and non-essential amino acids. Owing to the fact that pulses are rich in lysine but deficient in methionine, while cereals contain a high level of methionine but lack lysine, an effective approach to address unbalanced amino acid composition and improve the nutritional value of plant-proteins involves combining cereals and pulses that complement each other in terms of amino acid profiles (McDermott & Wyatt, 2017).

Pulses are also recognized by their low fat content that range from 1 to 4%. In addition, they contain minerals (iron, potassium, calcium, phosphorous, zinc), water-soluble vitamins, and lipid-soluble vitamins like folate, riboflavin and thiamine, however, they are poor source of vitamin C (Iriti & Varoni, 2017).

Despite their nutritional benefits, it is important to note that the presence of some anti-nutrient compounds such as phytate, tannin and phenol, can reduce the absorption of minerals by the body as well as iron and zinc. Yet, if consumed with food containing vitamin C; pulses can be a good source of iron due to its increased absorption in presence of this vitamin (Parveen et al., 2016).

As the demand for pulse products and their fractions such as proteins and flours is increasing, the pulse processing industry is experiencing significant growth (Thakur et al., 2019). Various processing methods such as soaking, dehulling, milling, germination, fermentation, and boiling are used in order to enhance the digestibility of pulses besides reducing anti-nutrient components (Ferawati et al., 2019). However, the most common process of pulses preparation is to cook whole grains in boiling water (Malcolmson & Han, 2019).
Table 2. Amino acid (AA) composition (mg/g protein) of some common types of pulses.

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Chickpea</th>
<th>Lentil</th>
<th>Pea</th>
<th>Common Bean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoleucine</td>
<td>44.32</td>
<td>43.20</td>
<td>42.72</td>
<td>41.95</td>
</tr>
<tr>
<td>Leucine</td>
<td>74.88</td>
<td>76.32</td>
<td>68</td>
<td>76.24</td>
</tr>
<tr>
<td>Lysine</td>
<td>68.48</td>
<td>71.84</td>
<td>75.20</td>
<td>72.08</td>
</tr>
<tr>
<td>Methionine</td>
<td>10.40</td>
<td>8.00</td>
<td>9.12</td>
<td>10.59</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>57.28</td>
<td>52.32</td>
<td>45.92</td>
<td>52.22</td>
</tr>
<tr>
<td>Threonine</td>
<td>37.60</td>
<td>39.68</td>
<td>40.64</td>
<td>39.73</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>#</td>
<td>#</td>
<td>#</td>
<td>0</td>
</tr>
<tr>
<td>Valine</td>
<td>45.44</td>
<td>50.08</td>
<td>47.04</td>
<td>45.97</td>
</tr>
<tr>
<td>Histidine</td>
<td>26.4</td>
<td>27.36</td>
<td>22.88</td>
<td>28.37</td>
</tr>
<tr>
<td>Cysteine</td>
<td>11.84</td>
<td>9.12</td>
<td>11.2</td>
<td>8.51</td>
</tr>
<tr>
<td>Tyrosine</td>
<td>29.28</td>
<td>32.64</td>
<td>27.36</td>
<td>25.29</td>
</tr>
<tr>
<td>Arginine</td>
<td>94.08</td>
<td>86.88</td>
<td>95.2</td>
<td>56.88</td>
</tr>
<tr>
<td>Alanine</td>
<td>43.36</td>
<td>43.04</td>
<td>40.8</td>
<td>41.95</td>
</tr>
<tr>
<td>Aspartic Acid + Asparagine</td>
<td>116</td>
<td>115.68</td>
<td>109.6</td>
<td>119.82</td>
</tr>
<tr>
<td>Glutamic Acid + Glutamine</td>
<td>158.56</td>
<td>165.92</td>
<td>161.44</td>
<td>148.01</td>
</tr>
<tr>
<td>Glycine</td>
<td>40.16</td>
<td>42.24</td>
<td>40.48</td>
<td>37.96</td>
</tr>
<tr>
<td>Proline</td>
<td>42.08</td>
<td>42.72</td>
<td>39.04</td>
<td>35.70</td>
</tr>
<tr>
<td>Serine</td>
<td>50.88</td>
<td>52.64</td>
<td>43.36</td>
<td>55.57</td>
</tr>
<tr>
<td>Total AA</td>
<td>951.04</td>
<td>959.68</td>
<td>920</td>
<td>896.83</td>
</tr>
<tr>
<td>Total essential AA (in bold)</td>
<td>364.80</td>
<td>368.80</td>
<td>351.52</td>
<td>367.15</td>
</tr>
<tr>
<td>Non-essential</td>
<td>586.24</td>
<td>590.88</td>
<td>568.48</td>
<td>529.68</td>
</tr>
</tbody>
</table>

Adapted from (Rajpuhot & Li, 2023). # indicates “not reported”.

Recent processing methods are also being applied as well as emerging techniques such as microwaving, extrusion, and micronization. They can be used also to produce pulse flours and fractions such as pulse starch flours, fibers, proteins isolates and concentrates among others (Farooq & Boye, 2011). Isoelectric precipitation and alkaline extraction are the main methods used for the wet separation of pulse flour into proteins, starches, and fibers (Boye et al., 2010; Singhal et al., 2016). The isoelectric precipitation and alkaline extraction procedures are not ecologically friendly given that their application involve of the use of strong chemical solvents. On the other hand, there have also been reports of other approaches, including salt and enzyme-assisted extraction (Sá et al., 2022).

Despite the increasing interest in pulses, it is noteworthy that the application of pulses in food concepts remains limited, due to the fact that their use presents various challenges. The most common barriers of the use of pulses is 'beany' and 'off flavors', texture issues due to the absence of gluten, and gastrointestinal symptoms that may arise from excessive consumption (Escobedo & Mojica, 2021). Thereby, the major use of pulse flours and fractions like proteins isolates and
concentrates is based on the enrichment of various food products such as baked goods, cookies, and pasta and meat substitutes (Patrascu et al., 2017). There is a wide literature investigating the application of pulses in food products. **Table 3** presents some examples of these works focusing on the ones that deals with the use of different types of pulses and their fractions in the elaboration of food goods.

The use of plant-based ingredient as a source of protein in food industry depends on their nutritional, sensory and techno-functional characteristics. The techno-functional properties can be defined as the physical and chemical properties of an ingredient that influence its behavior when interacting with other components during processing, storage, consumption, and digestion (Y. Wang et al., 2023). Techno-functional properties include water and oil holding capacity, foaming and emulsifying properties, rheological and gelling properties. These properties determine different properties of the final product, including structural and sensory aspects, thus determining its final structure. **Figure 3** presents a diagram with the techno-functional properties of some common plant-based sources of proteins and their effect in food characteristics. For instance, water/oil holding capacities influence the juiciness and cookability of plant-based yogurts and meat analogues (Grasso et al., 2020). Good gelling properties are required for the elaboration of sausages and cheese analogues (Jeewanthi & Paik, 2018), meanwhile good rheological properties are required for baby-food and soups (Bencini, 1986). On the other hand, foaming properties are useful for ice cream and fluffy cakes preparation (Jarpa-Parra et al., 2017), meanwhile emulsifying properties are useful for dressing, sauces and meat analogues (Kyriakopoulou et al., 2021).
Table 3. An overview of the application of pulse flours and fractions as sources of proteins in plant-based food production.

<table>
<thead>
<tr>
<th>Food Category</th>
<th>Type</th>
<th>The main plant-based ingredients used</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baked Products</td>
<td>Bread</td>
<td>Chickpea flour, pea isolate, carob germ, soy flour</td>
<td>(Miñarro et al., 2012)</td>
</tr>
<tr>
<td></td>
<td>Bread</td>
<td>Substitution of 15% of wheat flour by high protein ingredients (pea isolates and fava bean concentrates)</td>
<td>(Hoehnel et al., 2019)</td>
</tr>
<tr>
<td></td>
<td>Bread</td>
<td>Incorporation of pulse purée (chickpea, white bean, black bean, and red bean) into crispbread</td>
<td>(Szulc &amp; Galus, 2024)</td>
</tr>
<tr>
<td></td>
<td>Cereal Bars</td>
<td>Flours of cowpea and pigeon pea</td>
<td>(Maia et al., 2021)</td>
</tr>
<tr>
<td></td>
<td>Crackers</td>
<td>Development of 100% pulse-based cracker snack using several pulse fractions that included green and red lentil, among other flours and proteins</td>
<td>(Jay et al., 2010)</td>
</tr>
<tr>
<td></td>
<td>Crackers</td>
<td>Incorporation of chickpea flour in wheat-based crackers</td>
<td>(Kohajdová et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>Cakes</td>
<td>Substitution of wheat flour with lentil flour to produce a layer cake and a sponge cake.</td>
<td>(Hera et al., 2012)</td>
</tr>
<tr>
<td></td>
<td>Cake/Muffins</td>
<td>Replacing egg/milk protein by lentil proteins on angel cake and muffin cake.</td>
<td>(Marcela Jarpa-Parra et al., 2017)</td>
</tr>
<tr>
<td></td>
<td>Pasta</td>
<td>Substitution of 40% of wheat semolina by mung bean flour and soy flour.</td>
<td>(Balasooriya &amp; Wickramasinghe, 2018)</td>
</tr>
<tr>
<td></td>
<td>Pasta</td>
<td>Development of gluten free pasta using pulse proteins such as fava bean and pea proteins</td>
<td>(Shukla et al., 2021)</td>
</tr>
<tr>
<td></td>
<td>Pasta</td>
<td>Elaboration of pasta by conventional extrusion and extrusion cooking of 100% yellow lentil flour.</td>
<td>(Bresciani et al., 2021)</td>
</tr>
<tr>
<td></td>
<td>Meant analogues</td>
<td>Transformation of pea protein into a meat analogue through high moisture extrusion</td>
<td>(Sun &amp; Arnt, 2012)</td>
</tr>
<tr>
<td></td>
<td>Meat analogue</td>
<td>Preparation of meat analogue with hempseed protein concentrate, in combination with wheat gluten, and chickpea protein concentrate.</td>
<td>(Zahari et al., 2023)</td>
</tr>
<tr>
<td></td>
<td>Meat analogue</td>
<td>Preparation of meat analogues using protein-rich flours from pea and lentil</td>
<td>(Usman et al., 2023)</td>
</tr>
<tr>
<td>Dairy Products</td>
<td>Yoghurt</td>
<td>Preparation of yoghurt from pulse flours and pulse milk.</td>
<td>(Jamalullail et al., 2023)</td>
</tr>
<tr>
<td></td>
<td>Yoghurt</td>
<td>Fermentation of rice, lentil and chickpea flours</td>
<td>(Pontonio et al., 2020)</td>
</tr>
<tr>
<td></td>
<td>Yoghurt</td>
<td>Fermentation of African yam bean flour.</td>
<td>(Aminigo et al., 2009)</td>
</tr>
<tr>
<td></td>
<td>Cheese</td>
<td>Development of plant-based cheese analogues using pea and faba bean flours</td>
<td>(Ferawati et al., 2021)</td>
</tr>
<tr>
<td></td>
<td>Cheese</td>
<td>Elaboration of cheese analogues based on zein protein isolate and chickpea protein concentrate</td>
<td>(Grasso et al., 2023)</td>
</tr>
<tr>
<td></td>
<td>Beverage</td>
<td>Development of chickpea beverage as alternative to soy beverages.</td>
<td>(S. Wang et al., 2018)</td>
</tr>
</tbody>
</table>
As mentioned previously, wheat and soy constitute the main plant-protein source currently used for plant-based food application. In this context, several studies investigated the techno-functional properties of these plant-proteins (Peng, Kersten, et al., 2020; Peng, Putu, et al., 2020; Zhang et al., 2021). These researches pointed out that wheat and soy exhibit favorable water retention, emulsifying, foaming, and gelling properties, which can be manipulated with several factors like pH and ionic strength, hence this allowed their application in plant-based food industry. On the other hand, considering the growing interest in affordable, less processed plant-protein sources that are less allergic, pulse flours can be a viable alternative to soy and wheat for the development of various plant-based concepts (Bravo-núñez & Gómez, 2021; Maia et al., 2021). Pulse flours are obtained by milling whole or dehulled pulses and are considered as nutrient dense and less processed ingredient when compared with proteins isolates and concentrates. Previous studies have been conducted to evaluate the functionality of different types of pulse flours in order to assess the suitability for developing new food products. Authors pointed out that pulse flours exhibit diverse functional properties that make them suitable raw ingredient for developing various food categories (Ferawati et al., 2021; Motta & Zhang, 2019; Patrascu et al., 2017; Vasilean et al., 2018). For instance, Patrascu et al., (2017) evaluated the functional properties of pulse flours obtained from broad bean, red and green lentil in order to identify their potential application in spreadable food products. As compared to soy protein concentrates, the pulse flours showed higher values for water and oil binding capacities, and emulsifying properties. In addition, authors reported that the results of

**Figure 3.** Diagram with the techno-functional properties of the main sources of plant-proteins (oil seeds, cereals and pulses) and their effect on food formulation and characteristics. LGC: Least gelation concentration. Adapted from (Rajpurohit & Li, 2023).
rheological shear tests indicated a better stability of the suspensions based on pulse flours compared to soy protein concentrates. Nonetheless, it should be taken into account that the development of new plant-based product involves the application of different processing treatments, including the addition of several types of ingredients for technological, nutritional or sensory objectives. However, there is very little information related to the functional properties pulse flours and how they can be modulated by processing and formulation conditions such pH and ionic strength.

To design and develop new products that, in addition to provide specific health benefits, are acceptable to the consumer and more sustainable, a top priority is achieving the structural and sensory properties of the estimated product using ingredients that are less artificial and more eco-friendly. However, sensory characteristic in particular flavor and texture are still one of the big challenges to be overcome by alternative protein manufacturers (Benković et al., 2023; Singh, 2017). From this standpoint, besides studying the effect of the application pulses in the structural properties of different food categories, several researches investigated the effect of the application of pulse flours on the sensory characteristics and consumer acceptance of plant-based products. For instance, Proserpio et al., (2020) assessed the impact of using pulse flour on sensory properties of snack formulations. Authors highlighted that pulse-based snacks were moderately accepted by consumers. Similarly, Millar et al., (2017) studied the effect of supplementation with pulse flours (pea and bean) on the sensory characteristics of crackers and they reported that pulse crackers were highly preferred by the consumers. Likewise, S. Wang et al., (2018) who elaborated a novel plant-based beverage with chickpea, noted that sensory analysis revealed that the fresh chickpea beverage was as acceptable as the soy one.

Given their versatile composition, pulse flours might be used in the development of appealing protein-enriched and more sustainable food options, which may fill the existing gap in the plant-based food market. Considering this, and with the goal of facilitating the application and modulation of pulse flours, it is important to explore the effect of changes in the processing conditions and concentration of additional ingredients on the techno-functional and sensory properties of pulse flours and products. In this context, we hypothesize first that the techno-functional properties of pulse flours and pulse pastes and gels can be modulated by varying pH and calcium content. Secondly, we hypothesize that changes in natural ingredients content such as lemon juice, oil, and salt might be useful in the manipulation of pulse-based products in terms of mechanical and sensory properties.
1.3 Towards more plant-based: insights from a consumer perspective

Given the need for the transition towards healthy and more sustainable food consumption, a greater understanding of consumers’ food choices is a crucial task for food industry and policy makers in order to promote this transition. Several changes have been observed in consumer preferences seeking for healthier food options besides of preferring more sustainable options (Clem, J., & Barthel, 2021; Culliford & Bradbury, 2020). In addition, it is worth noting that success in product development is intricately linked to comprehending consumer behavior and how it is delineated.

In general, consumers’ food choices are an outcome of various factors dealing with personal traits of the consumer (the physiological, psychological and sociological aspects of consumers) and product characteristics. Moreover, food choice is complex task that involves the selection and decision that consumers make concerning food; including aspects such as what, how, when, where and with whom to eat. An outline of the different factors and aspects influencing food choice behavior is shown in Figure 4 (Köster, 2009). These psychological were categorized into three primary groups: i) cognition, emotion, motivation, and decision-making, ii) memory, past experiences, and learning, and iii) neophobia and personality traits. Accordingly, there has been an expansion of sensory research into exploring consumers' perspectives, along with the introduction of novel methodologies aimed at examining the impact of various factors on the decision-making process (Köster, 2009). Therefore, different tools and methods are used in sensory and consumer research with the goal of comprehending consumers’ needs and preferences as well as understanding the mechanisms of product perception (Figure 5). These methods has been used over time for new product development and optimization, as well as for estimating the interactions among ingredients and their influence on product characteristic in order to develop products that would be as widely accepted as possible (Meiselman et al., 2022). This, in turn, promotes methodologies for more effectively engaging consumers and enhancing product quality.
Figure 4. Principal factors affecting consumers’ food choice and behavior. From (Köster, 2009).

Figure 5. Examples of methods used in sensory and consumer research.
Accordingly, when talking about changes in consumers’ food consumption to healthier and more sustainable diets by adopting more plant-based consumption, it becomes necessary to gain a deeper understanding of consumers’ responses to plant-based products and the effect of different factors that can drive their opinion towards such kind of products. Understanding consumers’ behavior or choice will enable policy makers and industry to provide novel food options that meets consumer needs and preferences.

Personal traits such as motivations, experiences and attitudes of consumers affect largely their food choice. Consumers’ attitudes, expectations and opinions are of high importance when talking about healthy and sustainable food. Indeed, they can act as drivers of or barriers to changes in food consumption practices. Consumer attitude is a composite of cognitive (individual beliefs), affective (feelings), and behavioral intention toward an object. In fact, consumer opinions and attitudes regarding a certain product may affect the choice of food before consumption (expectations) and the acceptance or rejection of that meal after consumption (Perez-Cueto et al., 2022). After that, whether the product meets the consumer expectations will determine how they would react to it. Finding out how the confirmation or non-confirmation of expectations influences food acceptance is the question that emerges from a practical standpoint. For instance, buying plant-based food might be linked to the level in which consumers are interested in a healthy diet and healthy planet, but after consumption, consumers’ decision can be highly affected according to the degree of acceptance of this product (Appiani et al., 2023).

Previous works highlighted the importance of the attitude towards reducing meat consumption in consumers’ transition towards more plant-based food consumption (Estell et al., 2021; Realini et al., 2023). It has been proposed that consumer dietary choices are largely impacted by their concerns about health, environment and ethical beliefs, which can affect attitudes towards plant-based food alternatives (Kopplin & Rausch, 2022). Regarding health concerns, for instance, interest in reducing meat consumption can be a driver for following a determined diet such as plant-based diet and therefore selecting such type of products. Environmental concerns refer to consumers’ level of awareness about the impact of human activities on the environment, and the importance of protecting the environment (Kopplin & Rausch, 2022). In this sense, environmentally conscious consumers are supposed more likely to have a positive attitude toward plant-based food because they believe that switching to a plant-based diet is generally an environmentally friendly choice, because plant-based diets typically have a lower environmental footprint than animal agriculture (Perez-Cueto et al., 2022). Consumers’ ethics
refer to the moral principles and standards that guide behavior of individuals or groups as they obtain, use, and dispose of goods and services, thus driving consumers’ behaviors as corresponding their ethics or not (Banovic et al., 2019). Some works reported that the moral and ethical concerns related to both the environmental impact and animal welfare played an important role in consumers’ meat avoidance behavior (Araújo et al., 2022).

When talking about market success of plant-based products, consumer acceptance is a crucial task. Taste is very important when it comes to food (Fiorentini et al., 2020). Thus, the acceptance of some alternative to meat sources of proteins is highly related to the success in recreating as similar as possible flavor and texture of meat products (Hwang et al., 2020; Michel et al., 2021). Moreover, taste expectations have the potential to impact the real taste experience, which in turn might impact the intention to buy following the initial tasting (Banovic et al., 2022). During last years, a great number of research works have focused on assessing the acceptance of different plant-based food reporting that product properties including taste primarily, besides of the lack of sensory appealing, are still challenging and preventing the acceptance of this kind of (Giacalone et al., 2022; Hwang et al., 2020; Michel et al., 2021). Consumers of this type of products demand alternatives that are as tasty as those of animal protein, with a similar texture and functionality (Appiani et al., 2023). Furthermore, meat attachment and the good taste of meat are considered as the main barriers among omnivores for the limited inclination to reduce meat consumption and embrace more plant-based products (Graça et al., 2015; Kopplin & Rausch, 2022)

Changes in the formulation of alternative products can decrease or increase their acceptability, especially when consumers prefer the characteristics of the original product. Plant-based products can have different textures and flavors, depending on the protein source used. Moreover, consumer acceptance can vary according to personal preferences, but it may also vary according to the type of product, its ingredients and the information offered in relation to the product (Türker et al., 2024). For instance, a study that evaluated consumers attitude toward pulses and cereals suggested that consumers may have different preference patterns for different sources of plant-based proteins (Melendrez-Ruiz et al., 2023). Similarly, a previous study conducted by Tarrega et al., (2017) indicated that consumers showed different preference patterns for different sources of fiber. In this context, understanding how the plant-protein source information may impact consumer acceptance is crucial to the success of plant-based product.
Various aspects of perception related to the evaluated product, such as healthiness and naturalness, that deal with the nutritional factor of the product have been acknowledged in order to gather feedback about consumer behavior and opinion (Hwang et al., 2020). Furthermore, it is important noting that a wide range of highly processed ingredients and additives such as protein isolates and concentrates are used in food industry in order to achieve the estimated properties of the products (Benković et al., 2023). However, the large list of ingredients and their nature have an impact on how the product is perceived by the consumer and may have an impact on their decision. Thus, understanding consumer perceptions elicited by the product is key for industry and policy makers for the development of products and communication strategies that meet consumers’ preferences. In this context, several works have shown that consumer perception of aspects such healthiness, sustainability and eco-friendliness can affect negatively or positively consumers decisions and choice of food products (Hartmann et al., 2022; Van Bussel et al., 2022). Similarly, other authors reported that fear from protein deficiency and consumers’ intention to avoid artificial and highly processed products were behind the low willingness of consumers to increase plant-based food consumption. Some authors suggested that these consumers perceive the meat products or animal sources of proteins as healthier since they are rich in protein and they consider them as less artificial (Kopplin & Rausch, 2022; Pohjolainen et al., 2015; Sendhil et al., 2024; Varela et al., 2022). Besides studying consumers’ acceptance of food products, emotional response has been integrated into sensory and consumer research with the purpose of improving the understanding of total consumer experiences and product differentiation (King et al., 2010; Ng et al., 2013). Evaluation of emotional response provides additional and sometimes divergent information about a consumer's reaction to different products, which can be crucial to their choice (Varela & Ares, 2018). Additionally, emotions can be involved in the development or design of products and can be used to identify the outcome of changes in the product under formulation (Varela & Ares, 2018). Ng & Hort (2015) highlighted the need to connecting the emotional response of consumers to sensory attributes in order to improve comprehension and build a product category's emotional signature. Thus, comprehending how flavor, smell, and visual elements of a product prompt subconscious sensations and emotions that eventually drive hedonic measures and choice behavior provides valuable information when considered with sensory analysis.

Methods such as self-reported measurements, are considered as affordable and informative methods for emotions evaluation. Verbal and non-verbal self-reported methods have widely
been used to assess different emotions components such as appraisal, action tendencies and subjective feelings (Ng & Hort, 2015). Different lexicons such us Geneva Emotion and Odor Scale (GEOS) and EsSense Profile were developed and translated to other languages in order to assess verbal self-report measurements of emotions (Chrea et al., 2009; King et al., 2010). The EsSense Profile, containing a list of 39 emotions associated with products’ consumption, was designed by King & Meiselman (2010) as shown in Table 4. After that, (Nestrud et al., 2016) developed and validated a shorter version from the same lexicon composed of 25 emotions known as EsSense25 (Table 4). Several studies have used the EsSense Profile questionnaire because it is cost-effective, easy to use and interpret and covers a wide range of emotions, providing valuable information on consumer perceptions of various food (Chaya et al., 2015; Mora et al., 2018). Later, different lexicons have been developed for specific food categories. For example, (Orr et al., 2023) elaborated a specific lexicon containing 24 emotion categories to meat and plant-based burger patties.

For further enabling the global shift towards less reliance on animal-based products and more sustainable food system, evaluation of consumers’ acceptance of the alternative products provide crucial information that should be considered. Understanding consumers’ response plant-based to products is essential to increase the acceptance of these new products. Accordingly we hypothesize that the attitude towards meat reduction and the information about the source of plant-protein may affect consumers’ expectations to plant-based products. Moreover, we hypothesize that the evaluation of self-reported emotions besides of consumers’ perception of healthiness, naturalness and sustainability of plant-based food provide valuable information beyond liking.
### Table 4. Emotion lexicon EsSense Profile according to King & Meiselman (2010). Emotion terms with (*) represent the common terms selected for the new Emotion lexicon EsSense25 Profile according to (Nestrud et al., 2016).

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
<th>Unclassified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active*</td>
<td>Bored*</td>
<td>Aggressive*</td>
</tr>
<tr>
<td>Adventurous*</td>
<td>Disgusted*</td>
<td>Daring</td>
</tr>
<tr>
<td>Affectionate</td>
<td>Worried*</td>
<td>Eager</td>
</tr>
<tr>
<td>Calm*</td>
<td></td>
<td>Guilty*</td>
</tr>
<tr>
<td>Energetic</td>
<td></td>
<td>Mild*</td>
</tr>
<tr>
<td>Enthusiastic*</td>
<td></td>
<td>Polite</td>
</tr>
<tr>
<td>Free*</td>
<td></td>
<td>Quiet</td>
</tr>
<tr>
<td>Friendly</td>
<td></td>
<td>Steady</td>
</tr>
<tr>
<td>Glad</td>
<td></td>
<td>Tame*</td>
</tr>
<tr>
<td>Good*</td>
<td></td>
<td>Understanding*</td>
</tr>
<tr>
<td>Good-natured*</td>
<td></td>
<td>Wild*</td>
</tr>
<tr>
<td>Happy*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interested*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joyful*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loving*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nostalgic*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peaceful</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pleasant*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satisfied*</td>
<td></td>
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<tr>
<td>Secure*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 1.4 Spanish perspective on the adoption of plant-based products

A complete switch to plant-based diet without animal-based product may not be a realistic path, however it can be an effective step in the transition towards more sustainable and healthy food diets by decreasing animal-based demand and consumption. Indeed, changes in consumers’ choice remain a voluntary behaviour that depend mainly on consumers’ decision. For instance, certain consumers, referred as flexitarians, have shifted towards more sustainable dietary patterns by reducing their meat intake instead of completely replacing it, nevertheless omnivores reported their low willingness to reduce meat consumption. Furthermore, previous studies reported that flexitarians and vegetarians showed positive attitude towards plant-based products as compared to omnivore consumers (Cliceri et al., 2018; Malek & Umberger, 2021; Noguerol et al., 2021). Findings from Lantern, (2019) revealed an increase in the adoption of...
dietary patterns with less meat consumption in Spain, encompassing 0.5% of individuals following a vegan diet, 1.5% adhering to a vegetarian diet, and 7.9% identifying as flexitarians.

Previous studies analysed meat consumption and consumer attitudes in Spain besides of the main concerns for the potential reduction in meat consumption. Authors pointed out that various factors, including health concerns, environmental concerns and ethical considerations related to current meat production methods and animal welfare could influence the attitudes and perceptions of Spanish consumers towards this crucial element of their diet and gastronomic culture (Font-i-Furnols & Guerrero, 2022). Another study revealed that 63% of Spanish consumers surveyed in a recent study said they would try cultivated meat, and 46% said they would buy it. The three primary reasons behind the willingness to reduce meat consumption and consume cultivated meat were found to be animal welfare, environmental concerns and curiosity (Munné, 2020; Rombach et al., 2022).

Nevertheless, it is important to note that Spain remains one the most consuming countries of meat as compared to other European countries (FAO, 2021b). Spain projected a high meat production reaching 7.6 million tonnes in 2020, showing an increase of +5.1% over 2019 (MAPA, 2021). Moreover, 42% of surveyed Spanish consumers stated that they do not think about the animal when buying and consuming meat (Smart protein, 2021). Furthermore, Font-i-Furnols & Guerrero, (2022) pointed out that, besides the hedonic factor, the main drivers of meat consumption among Spanish consumers are their consideration of the importance of nutritional characteristics of meat, and its perception as a healthy and essential component of a balanced diet. Another study explored consumer awareness, knowledge and attitudes towards a plant-based diet in European countries including Belgium, Denmark, the Netherlands and Spain. The study revealed that Spanish consumers showed the lowest level of consumer awareness, knowledge and attitudes towards a plant-based diet as compared to the other consumers from the other European countries (Faber et al., 2020).

In Spain, a new law that includes guidelines for the ethical treatment of animals has been recently established (Jefatura del Estado, 2023). The law addresses regulations that impact animal farming, including new values for the maximum density of animals in farms and conditions regarding environmental factors besides of the welfare regulations that encompass animals in the farming industry. From a consumer perspective, this law is expected to have an effect on interactions with animals and products derived from them. For instance, the law's provisions regarding the treatment of animals in various contexts, such as pet ownership and commercial activities, can shape consumer perceptions of ethical and responsible animal
treatment within the food and agriculture industries. Nevertheless, to date, there is a no
treatment within the food and agriculture industries. Nevertheless, to date, there is a no
knowledge about the impact of political interventions in the consumers’ awareness to adopt
more sustainable diets.

Focusing on young consumers is key in order to shape food systems toward a more sustainable
future. Several researches reported that young consumers showed higher acceptability of
alternative sources of proteins (Bryant & Barnett, 2020; Bryant & Sanctorum, 2021; Ford,
Zhang, et al., 2023; Giacalone & Jaeger, 2023; Siegrist & Hartmann, 2019). In addition, young
consumers were reported to be more interested by sustainability and environment than earlier
generations (Culliford & Bradbury, 2020; Ruzgys & Pickering, 2024). According to a study
conducted in China and Japan, young consumers' preferences for plant-based meat alternatives
were identical or even greater than those for traditional meat (Huang & Uehara, 2023).
Furthermore, a study conducted in Finland identified the millennials consumers as a group that
showed a notable interest in plant-based meat substitutes among other consumer groups
(Knaapila et al., 2022). Various researches have indicated that Generation Z shows higher
acceptance of plant-based diets. For instance, a study led by Sodexo revealed that 81% of
college students would choose a plant-based food offering, indicating a strong interest in plant-
based options among Generation Z (Sodexo, 2023). This generation's interest in plant-based
diets is driven by various factors, including health benefits, environmental concerns, and
willingness to reduce climate change impact (Faber et al., 2020; Ruzgys & Pickering, 2024).

Consumers’ segmentation has been applied in order to understand differences in attitudes and
interest towards different aspects such as sustainability attributes, animal welfare and new food
rejection (food neophobia). Food neophobia refers to the reluctance to eat unfamiliar foods
(Fernández-Ruiz et al., 2013; Pliner & Hobden, 1992). Meanwhile, food neophilia refers the
tendency to try and enjoy new foods. Most plant-based products available in the market can be
considered as new as compared to conventional products. Moreover, when it comes to the
acceptability of new meals or products, trust is crucial.

Although consumers demand on novel and sustainable food products is increasing, the
unfamiliarity with new food technologies and scepticism are reported among the frequent
drivers of low acceptability and purchase intention of new food products (Cox & Evans, 2008;
Frewer et al., 2011). A group of studies assessed the impact of food neophobia on consumers’
willingness to adopt a diet with alternative proteins based on insects and cultured meat (Baum
et al., 2021; Hwang et al., 2020). Authors reported a negative correlation between food
neophobia and the acceptance of animal protein substitutes; since consumers that are less open
to new food experience, namely “less neophilic”, perceive them as unfamiliar and uncertain. Additionally, a study conducted on British, Spanish and French consumers (Asioli et al., 2022) revealed that consumers who were less neophobic (more neophilic) were generally more willing to pay for cultured beef.

According to the above mentioned literature, Spanish consumers seem to be more conscious about health and environmental issues, besides of dietary changes related to reducing meat consumption, which impacts their decision to adopt more plant-based. However, there is less emphasis on animal welfare concerns in their food choices. This indicates that ethical considerations of animal welfare could play a key role in shaping consumer attitudes towards reducing meat intake and adopting plant-based diets. Thereby, consumers that are more ethically conscious or even affected by the new law related to animal welfare are more prone to support meat reduction and to choose more plant-based options. Moreover, consumers who are less concerned by animal welfare may not support the need to the transition towards plant-based consumption. Consistently, we expect that the effect of environment, health concerns and meat attachment on the choice of Spanish young consumers of plant-based food options be mediated by consumers’ ethics. Thus, a higher consideration of animal welfare by consumers would play the role of mediator; that is, strengthening the effect of environmental concerns, health concerns and meat attachment on expected liking and purchase intention of plant-based products. We thus hypothesize:

H1a: Environmental concerns have a significant effect on young Spanish consumers’ ethics.
H1b: Health concerns have a significant effect on young Spanish consumers’ ethics.
H1c: Meat attachment has a significant effect on young Spanish consumers’ ethics.
H2: Consumers’ ethics has a positive effect on expected liking and purchase intention of plant-based products.

By understanding these complex interplay of factors, marketers and policymakers can better tailor interventions and initiatives to promote sustainable and ethical dietary habits among a wider range of consumers.

In addition, we hypothesize that consumer’s diet and food neophilia or “consumers’ readiness to try new food concepts” can impact consumers’ expected liking and purchase intention of plant-based food.
H3: Food neophilia may affect consumers’ expected liking and purchase intention of plant-based food.

H4: Consumers’ diet may affect consumers’ expected liking and purchase intention of plant-based food.
1.5 Objectives

1.5.1 General aim

The general objective of this Thesis was to expand the knowledge about the physicochemical and sensory properties of plant-based ingredients and products relevant for the development of novel plant-based food and to determine consumers’ response towards such kind of products. In order to achieve this purpose, specific objectives were established in two main research topics. The first topic had the objective of exploring the techno-functional and sensory properties of pulse flours to assess their potential as base ingredient for developing novel plant-based products. The second topic was focused on studying consumers’ response to plant-based products in order to gain a deeper understanding on the factors involved in consumers’ acceptance of plant-based products. This knowledge facilitates the development of strategies aiming at better involving consumers in the transition towards healthier and more sustainable food consumption and improving the variety of plant-based products.

1.5.2 Specific objectives

Research topic 1:

- To investigate the techno-functional properties of different types of pulse flours (chickpea, lentil, red lentil and white bean) under different medium conditions of pH and calcium presence.
- To evaluate how the type of pulse (lentil, red lentil and chickpea) and the concentration of ingredients (flour, oil and lemon juice) influence the mechanical and sensory properties of pulse gels for the development of new plant-based products.

Research topic 2:

- To investigate the impact of environmental consciousness, health concerns, ethical concerns and dietary habits on consumers' attitude towards meat reduction.
- To determine the impact of the information about the source of plant-protein and the attitude towards meat consumption reduction on consumers’ response to plant-based products.
- To examine whether consumers’ attitude towards reducing meat consumption and food neophilia would affect young Spanish consumers’ expected liking and purchase intention of plant-based products.
• To investigate whether consumers’ ethics would mediate the effect of consumers’ concerns by environment, health and meat attachment on expected liking and purchase intention of plant-based products.
2. Chapter 2. Methodology
2.1. General Methodology Structure

To extend our knowledge of how pulse flours can contribute as main ingredients to the development of novel plant-based food products, and to examine consumers’ response to plant-based products, different research projects have been developed, each one connected to a specific publication (Table 5).

The methodology used in this Thesis depended mostly on the specific objectives. During the first two studies, the techno-functional and sensory properties of pulse flours and pulse products were evaluated. Pulse flours were selected among the common plant-based ingredients for their protein content, low allergicity, high availability and low cost in addition to being more eco-friendly. Once the techno-functional, rheological and mechanical properties of the pulse flours, pastes and gels under determined conditions were revealed, the second study addressed the effect of changes in the concentrations of natural ingredients (oil, lemon juice and salt) on the mechanical and sensory properties of plant-based products elaborated with pulse flours. The third study attempted to elucidate the consumers’ response towards plant-based products mediated by different factors (information about the source of plant-protein of the products and consumers’ attitude towards meat reduction). The fourth study aimed to understand the effect of individual attitudes and concerns of consumers on their response towards plant-based products by means of Structural Equations Modelling (SEM) analysis. The results of this last study are not yet published; however, this study is integral to the research presented in this Thesis and provides essential insights that contribute to a better understanding of the consumers’ response to plant-based products.
Table 5. Summary of the experimental design of the Thesis.

| General aim | To expand the knowledge about the possibilities of plant-protein ingredients and prototypes in the development of healthy and sustainable food products, and to determine consumers' response to such type of products besides on the factors that can affect their response. |
| Specific objectives | - To study the effect of pH and calcium on the techno-functional properties of four pulse flours (chickpea, lentil, red lentil, and white bean) and the rheological properties of their pastes and gels. | - To investigate how the mechanical and sensory properties of three different pulse gels (chickpea, lentil, or red lentil flour) vary with the ingredients (flour, oil, lemon, and salt content) | - To measure the impact of the information about the type of plant-protein and consumers’ attitude towards meat reduction on consumers’ response to different plant-based burgers. | - To understand how consumer preferences for plant-based products are influenced by ethical, environmental and health concerns, dietary habits and food neophilia, with a specific focus on the young Spanish consumers. |
| Samples | Chickpea, lentil, red lentil and white bean flours | Prototypes elaborated with chickpea, lentil or red lentil flours with oil, lemon and salt. | Three types of 100 % vegetal burger with different plant-proteins (soy, pea or wheat (seitan)) | Three types of 100 % vegetal burger with different plant-proteins (soy, pea or wheat (seitan)) |
| Participants | / 19 participants 368 participants 361 participants | | | |
| Manuscript | Effect of pH and calcium on the techno functional properties of different pulse flours, pastes, and gels. | Mechanical and sensory properties of pulse gels in the development of new plant based food | Evaluation of consumers’ response to plant-based burgers according to their attitude towards meat reduction | Understanding the effect of individual attitudes and concerns of consumers on their response towards plant-based products: A SEM analysis approach. |
2.2. Methodology of study 1: Effect of pH and Calcium on the Techno-functional Properties of Different Pulse Flours, Pastes, and Gels

The aim of the first study was to investigate the effect of pH and calcium on the techno-functional properties of different types of pulse flours (chickpea, lentil, red lentil and white bean). In order to achieve this objective, water holding capacity, emulsifying and foaming properties, rheological and mechanical properties of pulse flours, pastes and gels were studied at natural condition and when decreasing pH and adding calcium. The procedures used to evaluate the techno-functional properties of pulse flours, pastes, and gels under different conditions of pH and calcium are shown on Figure 6.

![Figure 6](image-url)

**Figure 6.** Procedures used to evaluate the techno-functional properties of pulse flours, pastes, and gels under different conditions of pH and calcium.
2.2.1 Samples

Four types of pulses have been used in the experiment for this study (chickpea, lentil, red lentil and white bean). Pulse flours were selected for their high protein content and as alternatives to the common plant-protein sources such as wheat and soy. Flours were provided by Dacsa Group (Valencia, Spain) and were stored in laboratory refrigerator at 4°C.

2.2.2 Procedure

Techno-functional properties of pulse flours were measured at natural condition and at modified conditions of pH and calcium presence. Natural condition that refers to the sample without any modification, pH 5 with/without calcium, and pH 3 with/without calcium were considered in this study. The pH adjustments were realized by adding a solution of citric acid while calcium content was changed using calcium chloride 2-hydrate (CaCl2.2H2O) at 0.025 g Ca/g flour.

2.2.2.1 Properties of the raw pulse flours

Water holding capacity, foaming properties and emulsifying capacity of pulse flours were determined. For each of the studied properties, measurement were replicated twice.

Water holding capacity refers to the ability of the flour to retain water during mixing or hydration. Water holding capacity plays a critical role in various food applications like dough development, texture, and shelf life. Flours that exhibit higher ability to retain water are capable to increase product hydration ensuring better quality by achieving the estimated consistency and texture, especially when juiciness is required (Traynham et al., 2007). In order to evaluate water holding capacity of pulse flours in this study, a mixture of 10% of flour/water was stirred for 30 s and allowed to stand for two hours. After that, the mixture was centrifuged. The supernatant was carefully removed and the hydrated sample was weighed. The Water holding capacity was calculated as the amount of water retained in g (difference in weight of the hydrated and dry flour) per gram of dry flour.

Emulsifying capacity refers to the ability to form dispersions of two (or more) immiscible liquids which are inherently thermodynamically unstable and tend to phase separate overtime via creaming, flocculation and/or coalescence. Higher emulsifying capacity is much desired in food industry for production of different food categories such as sauces and dressing (Aluko et al., 2009). To measure emulsifying capacity of pulse flours, a mixture of 20 mL of water, and 20 mL of sunflower oil with one gram of flour was homogenized using an Ultra-Turrax and centrifuged twice in order to separate the emulsified layer. The emulsifying capacity (%) was expressed as the volume of the emulsified layer divided by the total volume.

Foaming capacity refers to the ability of proteins to adsorb quickly at the air–water interface.
during whipping, whereas foaming stability is determined by the properties of the multilayer, cohesive film which surrounds the air bubbles and offers resistance against liquid drainage and droplet coalescence (Sreerama et al., 2012). The foaming properties are important for food such as ice cream and mousses. Foaming properties of pulse flours were determined by mixing 2% flour/water by an Ultra-Turrax. The mixture was transferred to a graduated cylinder to measure the volume of the foam immediately and over 30 min. Foaming capacity and foaming stability were expressed as the percentage increase in volume due to the foam at immediately and after 30 min, respectively.

2.2.2.2 Pasting profile of pulse flours

The pasting profile refers to the variation that occurs on the viscosity of a sample containing starch during the application of heating and stirring treatments. The pasting profile of flours reflects the process of gelatinization of the starch granules during heating. The pasting temperature (temperature when starch swells) and the values of the viscosity during heating and after cooling are obtained from the pasting profiles. They are useful to understand and control the physical properties of products where a starch-based ingredient is included. The viscosity profile of pulse flours was assessed during the thermo-mechanical processing of the 7.5% flour/water using a starch paste cell adapted to a controlled stress rheometer (ARG2, TA Instruments, Cheshire, UK). Viscosity values were registered while shearing the mixture at constant shear (160 rpm) and the temperature was set at 50 °C for 1 min, then increased to 90 °C during 2.83 min, it was maintained at 90 °C for 5 min, and finally decreased to 50 °C. Values of the pasting temperature, maximum viscosity during heating to 90 °C, and final viscosity after cooling to 25 °C were obtained from the curves. Subsequently, the pastes obtained were refrigerated at 4°C during 24h to evaluate the viscoelastic properties.

2.2.2.3 Viscoelastic properties of pulse flour pastes

The viscoelastic properties of pulse flour pastes were determined using (RheoStress 1, Haake, Germany) using a 60 mm parallel plate system with a 1 mm gap. Stress sweeps were performed at 1 Hz from 0.001 to 10 Pa to determine the linear viscoelastic region of the samples; then, frequency sweeps were run from 10 Hz to 0.01 Hz. The values of the storage modulus (G'), the loss modulus (G'') and the loss tangent (tan δ) were recorded as a function of frequency.

2.2.2.4 Mechanical Properties of pulse flour gels

Measurements of mechanical properties offer quantitative data on the physical characteristics of food products. The response of the material structure is registered when a deformation is applied. Different types of deformation such as compression, penetration or shearing are applied to understand how food products will behave during consumption (cutting or eating).
A texturometer (TA/XT Plus, Stable Micro Systems Ltd., Surrey, UK) was used to measure textural properties of pulse flour gels.

Gel preparation: 15% flour/water was homogenized at 1100 rpm for 2 min then it was heated for 20 min at 90 °C with stirring at 1100 rpm. Subsequently, the water the mixture was cooled for 5 min at 100 rpm until it reached 65 °C. The resulting mixtures were stored at 4 °C for 24h. Resistance to penetration, Textural profile analysis, Compression up to rupture of gels were measured.

Penetration test was assessed using the sample gel in the cylindrical container. For each pulse and condition, two cylinders of two batches were measured. Using a 10 mm diameter cylindrical probe, the force was registered when the sample gel in the cylindrical container (height = 37 mm, diameter = 65 mm) was penetrated to 5 mm at 1 mm/s. The maximum force value was obtained as a measure of the resistance to penetration. For each pulse and condition, two cylinders of two batches were measured.

Texture Profile Analysis (TPA) was performed on gel cylinders (17 × 22 mm) using a 75-mm diameter flat aluminium disk and compressed twice (10%) at 1 mm/s. From the force-time curves, hardness (maximum force of the first compression) and springiness (distance ratio of the first to the second compression) were obtained.

Compression up to rupture assessed by compressing gel cylinders (17 × 22 mm) up to 50% of their original height using a 75-mm diameter flat aluminum disk. For each pulse and condition, eight cylinders were measured from two batches. The force and distance at rupture were obtained from the force-time curves to calculate the Young Modulus (E) (N/mm²)

2.2.3 Statistical analysis

A 2-way ANOVA (pulse type and condition) with interaction was applied to each parameter. Tukey test was used to determine the significance of the differences among conditions for each pulse type. Significance level of 0.05 was considered.

To summarize the differences among the treatments, Principal Component Analysis (PCA) was applied where the treatments (four pulse flours x five conditions) were the rows; the means of the parameters studied of the properties of raw pulse flours, pastes, and gels were the columns.
2.3. Methodology of study 2: Mechanical and Sensory Properties of Pulse Gels in the Development of New Plant Based Food

The aim of this study was to determine how different ingredients (flour, oil, lemon, and salt content) can affect mechanical and sensory properties of gels produced using three different pulse flours (chickpea, lentil, or red lentil flour). To reach this objective, the study was conducted on two phases. First, following a fractional factorial design with augmentation that allow the estimation of both linear and quadratic effects, as well as binary interactions of the factors, 17 formulations of pulse gels were elaborated and their mechanical properties were studied. After that, by selecting 6 formulations from each pulse type, sensory evaluation using the Flash profile method was conducted in order to characterize the sensory properties of the elaborated pulse gels. The Procedures used to evaluate the mechanical and sensory properties of pulse gels used this study are shown on Figure 7.

Figure 7. Procedures used to evaluate the mechanical and sensory properties of pulse gels in study 2.
2.3.1 Samples
Lentil, red lentil, and chickpea flours were used. All were whole-grain flours except red lentil flour, which came from dehulled lentils. The flours were stored at 4°C.
Mineral water, sunflower oil, lemon juice and salt were used as ingredients for gels preparation.

2.3.2 Procedure
Samples were prepared in a kitchen robot by varying the concentration of each ingredient in the following ranges: flour (15% to 17.5%), oil (0% to 2.8%), lemon (0% to 2.8%), and salt (1% to 1.4%) and 17 formulations were obtained for each pulse type.
The mixture was homogenized for 2 min and subsequently heated at 90 °C for 8 min while stirring, and then cooled for 6 min. After that, the mixture was stored at 4 °C for 24 h.

2.3.2.1 Mechanical Properties of Pulse Gels
Textural measurements of gels (texture profile analysis, compression up to rupture, resistance to penetration, and cutting test) were conducted using a texturometer (TA/XT Plus, Stable Micro Systems Ltd., Surrey, UK). Texture profile analysis and compression up to rupture test were performed on gel cylinders (height = 22mm, diameter = 17mm). From the force–time curves, mechanical parameters were obtained.
Regarding the resistance to penetration test, the force was recorded when the sample gel contained in the cylindrical container was penetrated to 5 mm at 1 mm/s. From the force-time curve, the value of the area under the curve was obtained to show the resistance to penetration.
For the cutting test, gel cylinders (height = 62 mm, diameter = 36 mm) were cut transversally at 100% at using a butter/wire cutter (A/BC) and the cutting force was obtained from the force-time curves.

2.3.2.2 Sensory Evaluation
Flash profile methodology was used to evaluate sensory differences among pulse gels. Flash profile is a technique that allows characterizing and quantifying sensory differences among a set of products without the need of using a trained panel. Flash Profile method was proposed by Dairou & Sieffermann (2002). It is a method where each participant selects and uses his/her own vocabulary to evaluate the whole product set comparatively and score it using intensity-sorting scales instead of using intensity scales (Bredie et al., 2017; Dairou & Sieffermann, 2002). For the data analysis, Generalised Procrustes Analysis (GPA) technique is usually the most helpful, since it plots each participant’s data in a consensus space created by grouping terms that are similar and adjusting them for scale usage (Bredie et al., 2017). Thus, this method may be effective for identifying and evaluating changes on characteristics of products during development process from sensory quality perspective.
In this study, the Flash Profile method was used to evaluate the sensory differences among pulse gels. Nineteen participants (fourteen women and five men) with previous experience in sensory evaluation evaluated the pulse gels.

For each pulse flour, six formulations varying in the amount of flour (low or high) and in the presence of the other two ingredients, oil or oil and lemon were studied. The salt concentration used (0.7%) was kept constant across samples and evaluations. Similarly to mechanical measurements, gels were prepared in kitchen robot, then transferred to a plastic container and stored at 4 °C for 24 h.

A first session was used to generate the list of terms of each participant through an individual interview where the participant compared 3 different pairs of gels and described the differences in appearance, flavor and texture. Later, the sensory evaluation of the gels was conducted over four different sessions. In three separate sessions (one per pulse flour), the sensory differences among the six gels produced with the same pulse flour but different formulation (flour, oil, and lemon content) were evaluated. In a fourth session, gels of different pulses were compared using two gels of each pulse. The two selected gels included the high amount of flour (17.4%), one without oil and lemon and the other one with both ingredients. In each session, participants evaluated sensory differences using ranking tests for each attribute in their own list.

2.3.3 Statistical Analysis

A 2-way ANOVA (pulse type and formulation) with interaction was applied to the data of the mechanical parameters of gels (hardness, gumminess, Young’s modulus, area of penetration, and cutting force). For each mechanical property, the model explaining its variation with the formulation (flour, lemon, oil, and salt) was established using a nonlinear stepwise regression (probability for entry and removal equal to 0.05). Response surface plots were used to visualize the variation of mechanical properties with the formulation in those models that were complex. Generalized Procrustes Analysis (GPA) was performed on the Flash Profile ranking data to generate the factorial map representing sensory differences among samples. The analyses were performed using XLSTAT version 2020.4.1 software (Addinsoft, New York, NY, USA). The response surface plots were performed using MATLAB version 2023.02 (Mathworks, Natick, CA, USA).
2.4. Methodology of study 3: Evaluation of Consumers’ Response to Plant-Based Burgers According to Their Attitude Towards Meat Reduction

This study aimed to 1: measure the impact of the information about the source of plant-protein on consumers’ response to plant-based burgers, 2: to assess the impact of consumers’ attitude towards meat reduction on consumers’ response to such products. An online questionnaire was used to evaluate the consumers’ expected liking; emotional response, healthy, processed and sustainable perception evoked by plant-based burgers. After that, consumers’ attitude towards meat reduction was evaluated using a questionnaire related to meat consumption reduction. A summary of the followed methodology in the study is shown in Figure 8.

Figure 8. Different sections of the online questionnaire used to assess consumer response in study 3.
2.4.1 Samples

The study utilized an image of a commercial plant-based burger as the stimulus, specifying the primary source of its plant-protein (soy, pea or wheat (seitan)). These plant-proteins were selected based on their prevalence in the Spanish market’s plant-based meat alternatives. Each sample was assigned a random 3-digit code and presented to participants in a randomized order.

2.4.2 Consumers’ Panel

A group of 368 consumers aged between 18 and 65 years old participated in this study. They were invited to participate in the study by means of advertisements at the universities.

2.4.3 Procedure

The questionnaire was elaborated using Compusense Cloud Software (Compusense, Inc 2023, Guelph, Ontario, Canada). Participants received a link to the questionnaire by email. The questionnaire was composed of two sections; the first section was concerned by questions related to the samples, while the second section was concerned by consumers’ attitude towards meat reduction. For better visibility of the questionnaire, participants were asked to use a tablet or computer to assess the survey.

In the first part, consumers were presented with each plant-based burger image and asked to evaluate expected liking using a 9-point hedonic scale labelled from “dislike extremely” to “like extremely”. Then, emotional response was evaluated using the EsSense 25 lexicon. For each source of plant-protein burger, using a CATA ballot, participants were asked to check all emotional terms that applied to the different plant-based burgers. After that, consumers were asked to rate their healthy, processed and sustainable perception of the samples on line scales of 10 cm length.

Regarding consumers’ attitude towards meat reduction, participants were asked to rate their degree of agreement with 32 statements using a 7-point Likert scale (from “strongly disagree” to “strongly agree”). The statements were related to diet, habits, ethics, hedonism, health and environment (Tarrega et al., 2020). Statements of the questionnaire were randomized in order to avoid bias.

2.4.4 Statistical Analysis

Firstly, consumers’ attitude towards meat reduction was analysed by Exploratory Factor Analysis (EFA) with Varimax rotation. This analysis allowed grouping the items in new dimensions, according to their most relevant factors. Cronbach’s alpha was computed to determine the internal consistency of the items of the complete questionnaire and of each dimension.
Consumers’ classes were obtained by Hierarchical Cluster Analysis and characterized by their mean values on the different dimensions. 1-way ANOVA was performed for each dimension to find out if there were significant differences between consumer classes by dimension. 2-way ANOVAs were performed for expected liking, healthy, processed and sustainable perception in function of the source of plant-protein and consumers’ classes with double interaction. Tukey tests were used for ANOVA significant factors, in order to test significant differences between means. Cochran test was applied to the CATA data on emotions to analyse the effect of the different sources of plant-protein on emotional response. Chi-square tests were applied for each of the emotion terms in function of consumers’ classes. After filtering the significant emotions according to Chi-square tests, a Correspondence Analysis was applied to emotions data containing the consumers’ classes in rows and the significant emotions in columns.
2.5. Methodology of study 4: Understanding the effect of individual attitudes and concerns of consumers on their response towards plant-based products: A SEM analysis approach.

The objective of this study was to offer insights into the intricate interactions between variables impacting consumers' attitudes and behaviours towards plant-based products, with a specific focus on the young Spanish consumers. Additionally, this study attempts to advance knowledge on how consumer preferences for plant-based products are influenced by ethical, health and environmental concerns, and food neophilia. A similar methodology to the online survey used in study 3 with slight modifications and additions was used.

2.5.1 Stimuli

The study utilized an image of a commercial plant-based burger as the stimulus, specifying the primary source of its plant protein (soy, pea or wheat (seitan)). These plant proteins were selected based on their prevalence in the Spanish market’s plant-based meat alternatives. Each sample was assigned a random 3-digit code and presented to participants in a randomized order.

2.5.2 Participants

A total of 486 participants aged between 18 and 35 participated in this study. However, data from 125 participants were excluded from the study due to poor internal consistency. Final sample included 361 participants (average age: 22.3 ± 2.6 years). Table 6 presents the sociodemographic characteristics of the participants. The study adhered to Declaration of Helsinki guidelines and was thoroughly explained in a consent form. All the participants were informed that all data would be anonymized and only aggregated results would be reported. Participants were advised to use a tablet or computer (instead of a mobile phone) for optimal visibility when completing the questionnaire. Before beginning to answer the questionnaire, all participants were required to agree to the informed consent statement shown on the screen.
Table 6. Sociodemographic characteristics of the participants.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Category</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Male</td>
<td>164</td>
<td>45.43%</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>197</td>
<td>54.57%</td>
</tr>
<tr>
<td>Diet</td>
<td>Mediterranean</td>
<td>316</td>
<td>87.53%</td>
</tr>
<tr>
<td></td>
<td>Flexitarian</td>
<td>28</td>
<td>7.76%</td>
</tr>
<tr>
<td></td>
<td>Vegetarian</td>
<td>13</td>
<td>3.60%</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>4</td>
<td>1.11%</td>
</tr>
<tr>
<td>Education</td>
<td>Health or Food</td>
<td>187</td>
<td>51.80%</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>174</td>
<td>48.20%</td>
</tr>
</tbody>
</table>

2.5.3 Procedure and Measures

Participants were invited to complete an online questionnaire created with Compusense Cloud Software (Compusense, Inc 2023. Guelph, Ontario, Canada), also used for data collection.

According to the hypothesised conceptual framework (Figure 9), the questionnaire consisted of several sections: the first section was dedicated to stimuli assessment (i.e., expected liking and purchase intention of plant-based burgers) and the second section included different questionnaires to evaluate individual consumer traits and attitudes (i.e., attitude towards reducing meat consumption, food neophilia, and sociodemographic traits).

Figure 9. Conceptual framework of study 4.

To assess expected liking and purchase intention, participants were shown the images of three plant-based burgers. Each image stimuli was accompanied by a description detailing the source
of its plant-protein. Participants were instructed to carefully observe each image before responding to the questions. For each image, they were first asked to rate their expected liking ("How much do you think you would like this burger?") on a 9-point hedonic scale, which ranged from "I think I would dislike it extremely" to "I think I would like it extremely" at opposite ends of the scale. Subsequently, they were asked to rate their purchase intention ("Would you buy this burger?") using a 5-point scale ranging from "Definitely I would not buy it" to "Definitely I would buy it" at the scale extremes.

Based on prior studies (Tarrega et al., 2020)(Moussaoui et al., 2023), four dimensions were considered to assess consumers’ attitude towards meat reduction. Participants were asked to express their agreement on a 7-point Likert scale (ranging from “strongly disagree” to “strongly agree”) with 15 statements reflecting motivations to reduce meat consumption: diet (4 items), health (4 items), environment (4 items) and ethics (3 items) (see Table 7). To minimize order bias, the order of the items in the questionnaire was randomised.

To assess food neophilia attitude of participants, a questionnaire including six items from a Spanish version of the Food Neophobia Scale (Fernández-Ruiz et al., 2013) was used. Participants rated their agreement with these statements on a 7-point Likert scale from “strongly disagree” to “strongly agree” (see Table 7).

Finally, participants provided information about their diet, age, gender, and education. Definitions of the common dietary choices in Spain were provided to help participants accurately identify their diets:

- **Vegan**: A diet exclusively comprising of food from plant origin, avoiding all animal origin products including meat, fish, eggs, dairy products, and derivatives.

- **Vegetarian**: A diet primarily based on food from plant origin but includes milk, dairy derivatives and/or eggs.

- **Flexitarian**: Essentially a vegetarian diet that occasionally includes meat or fish typically on a weekly basis.

- **Mediterranean**: An omnivorous diet predominated by plant foods but includes a variety of animal products.
Table 7. Items used for measuring attitude towards meat reduction and food neophilia.

<table>
<thead>
<tr>
<th>Item</th>
<th>Statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diet 1</td>
<td>I do not need to eat meat to have enough energy.</td>
</tr>
<tr>
<td>Diet 2</td>
<td>All things considered, meat is unnecessary in the human diet.</td>
</tr>
<tr>
<td>Diet 3</td>
<td>If I do not eat meat, I would feel strong</td>
</tr>
<tr>
<td>Diet 4</td>
<td>Eating meat is unimportant for a complete diet.</td>
</tr>
<tr>
<td>Environment 1</td>
<td>Eating meat has a negative impact on the environment.</td>
</tr>
<tr>
<td>Environment 2</td>
<td>By eating meat, I support an industry which is responsible for environmental damage.</td>
</tr>
<tr>
<td>Environment 3</td>
<td>By eating meat, I am also responsible for the problems associated with its production.</td>
</tr>
<tr>
<td>Environment 4</td>
<td>To eat meat is disrespectful towards life and the environment.</td>
</tr>
<tr>
<td>Health 1</td>
<td>Eating meat in excess has a negative impact on health.</td>
</tr>
<tr>
<td>Health 2</td>
<td>A diet with lots of meat can be harmful to health.</td>
</tr>
<tr>
<td>Health 3</td>
<td>If I ate less meat, my health would improve.</td>
</tr>
<tr>
<td>Health 4</td>
<td>Eating less meat is good for my health.</td>
</tr>
<tr>
<td>Ethic 1</td>
<td>It would be difficult for me to watch an animal being killed for food purposes.</td>
</tr>
<tr>
<td>Ethic 2</td>
<td>If I had to kill the animals myself. I would probably stop eating meat.</td>
</tr>
<tr>
<td>Ethic 3</td>
<td>If I saw an animal being killed, I would have problems eating it.</td>
</tr>
<tr>
<td>Food Neophilia</td>
<td>I do not trust new foods</td>
</tr>
<tr>
<td>Neophilia 2</td>
<td>Even If I do not know what is in a food, I try it.</td>
</tr>
<tr>
<td>Neophilia 3</td>
<td>At parties with food, I try new foods.</td>
</tr>
<tr>
<td>Neophilia 4</td>
<td>I am not afraid to try foods I have never tried before.</td>
</tr>
<tr>
<td>Neophilia 5</td>
<td>I am not very particular about the foods I eat</td>
</tr>
<tr>
<td>Neophilia 6</td>
<td>I will eat almost anything</td>
</tr>
</tbody>
</table>

2.5.4 Data analysis

The model postulated in Figure 9 was tested using Structural Equation Modelling (SEM) using AMOS 29.0 software.

Participants whose response variability was higher than 70% for items measuring attitude towards meat reduction and food neophilia were excluded to maintain data integrity and ensure good internal consistency.

For each consumer, the average of the scores given to the different items related to their attitude towards meat reduction and to the items related to food neophilia was obtained. According to the tertile values consumers were classified by the attitude towards meat reduction attitude in three three classes from less to more supporters. In the same way, Moreover, according to the food neophilia level, consumers were classified in three classes from less to more neophilic. Subsequently, Two-way ANOVAs with interaction were conducted to evaluate the effect of the type of plant-protein and consumers’ classification according to their attitude towards meat.
reduction and food neophilia level on the expected liking and purchase intention. XLSTAT (Addinsoft, 2023, New York, United States) was used as statistical software. A significance level of 0.05 was considered.

Internal reliability of each factor was further assessed by the Cronbach’s alpha coefficient. Following, a Confirmatory Factor Analysis (CFA) using Maximum Likelihood estimation was conducted in order to validate their applicability for testing the postulated model (Figure 9) in SEM. To establish convergent and discriminant validity, as well as reliability, of the measurement model we assessed the Composite Reliability (CR), Average Variance Extracted (AVE), where the threshold for these values are as follows: CR > 0.7 and AVE > 0.5. After validating the measurement model, a multi-group Structural Equation Modelling (SEM) was performed. The CFA and SEM model fit were evaluated through several goodness of fit indices, including: Chi-square by degrees of freedom (CMIN/DF), Root Mean Square Error of Approximation (RMSEA), Goodness of Fit (GFI), and Comparative Fit Index (CFI).
3. Chapter 3. Published Articles
3.1. STUDY 1

Effect of pH and Calcium on the Techno-functional Properties of Different Pulse Flours, Pastes, and Gels

Djemaa Moussaoui, Carolina Chaya, Celia Badia-Olmos, Arantxa Rizo and Amparo Tarrega

Food and Bioprocess Technology (2023).

DOI: 10.1007/s11947-023-03264-1.
Effect of pH and Calcium on the Techno-functional Properties of Different Pulse Flours, Pastes, and Gels

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KEYWORDS

Emotional response; Flour; Pulse; pH; Calcium; Techno-functional Properties; Plant-based Protein

HIGHLIGHTS

- The properties of the flours were affected by pH and calcium differently depending on the pulse.
- The water holding capacity and foaming properties of pulse flours are improved by lowering pH and adding calcium.
- The viscosity of pulse flour pastes is improved by lowering the pH to 5 and 3.
- The strengths and elasticity of the pulse gels were reduced when the pH was decreased and calcium was added except for white beans.
In this study, our objective was to show the effects of pH and calcium on the techno-functional properties of four pulse flours (chickpea, lentil, red lentil, and white bean) and the rheological properties of their pastes and gels. Five conditions were considered: a natural condition and four modifications (pH 3 and pH 5; with or without calcium addition). All measured properties varied with the type, condition, and the interaction among them. All flours exhibited high foaming capacity (44.3% - 78.8%) and emulsifying capacity (46.6% - 49.9%). The white bean flour showed a high water holding capacity (1.6 – 2.0 g/g), and the red lentil, lentil, and chickpea formed strong gels and high viscosity pastes. For the four pulses, the water holding capacity and foaming capacity of the flours and the viscosity of the pastes were improved by decreasing the pH (at 3 or 5) plus the addition of calcium. The hardness, elasticity, and resistance of gels obtained from pulse flour (except for white bean) were high when using natural conditions. Lowering pH resulted in a reduction of these parameters.
Chapter 3. Published Articles

1. INTRODUCTION

In recent years, the interest in plant-based products as a source of protein in the diet has been growing because of institutional recommendations and the willingness of some consumers to reduce animal-based products. Different motivations are behind the shift toward more plant-based products in human diets, such as sustainability, reducing the environmental footprint, animal welfare, and health (Pais et al., 2022; Tárrega et al., 2020; Singh & Sit., 2022). Soy and wheat are the leading plant-based proteins, but more recently the pea protein has also gained relevance due to the allergenicity of soy and wheat (Sun-Waterhouse et al., 2014). Research has been mostly conducted on these sources, and the knowledge of formulation and processing factors affecting gelling, emulsifying, or foaming properties has been key to develop new plant-based alternatives or analogues (Manassero et al., 2018; Lu et al., 2020; Aluko et al., 2009; Luo & Koksel, 2020; Peng et al., 2020). However, the low variability and lack of appealing textures and flavors are still the main barriers for consumers (Alcorta et al., 2021). Using more diverse plant-based ingredients has been proposed as a strategy to enhance the quality of alternative products. Other pulses with a high production volume worldwide, such as beans, chickpeas, and lentils (30.4, 17.2, and 7.2 million of tons per year, respectively), are now being considered as alternative sources of protein (Bravo-nez & Gómez, 2021). Chickpeas, beans, and lentils contain 20–30% protein (Shevkani et al., 2019), although this can vary among genotypes, germination, environmental conditions, and fertilizer use (Shevkani et al., 2019). Protein concentrates and isolates of these pulses provided interesting technological functionalities, such as foaming, emulsifying, and gelling capacity (Boye et al., 2010; Joshi et al., 2014; Karaca et al., 2011; Sosa et al., 2020). These properties vary depending on the pH and ionic strength, because they affect protein solubility, surface charge, and hydrophobicity. These effects are complex as they depend on the type and state of the protein (Manasero et al., 2018; Shevkani et al., 2019). The production of concentrates and isolates includes extraction and separation processes that make them expensive and/or less sustainable ingredients. The most used method is alkaline extraction combined with isoelectric precipitation, but harsh chemicals that can affect functional properties and make this process non-environmentally friendly (Mondor et al., 2022).

Flours are less processed ingredients, obtained by milling whole or split pulses. They still have a relatively high content of proteins but also contain starch that can provide additional properties under heating conditions. Most research and industry applications of pulse flours focus on the...
enrichment of bakery products, snacks, baby food, and sport food (Escobedo & Mojica, 2021; Maia et al., 2021; Motta & Zhang, 2019; Patrascu et al., 2017; Rachwa-Rosiak et al., 2015). However, pulse flours appear to be a good alternative base ingredient for new products, designing the product structure around the knowledge of base ingredient’s functional properties and how they can be modulated by processing and formulation conditions. Therefore, the objectives of this work are to study and compare the impact of pH and calcium conditions on the techno-functional properties of different pulse flours (chickpea, lentil red lentil, and white bean) and on the rheological properties of their pastes and gels to facilitate their application in the development of sustainable products with high protein content.

2. MATERIALS AND METHODS

2.1. Materials

Four types of pulse flour (chickpea, lentil, red lentil, and white bean) provided by Dacsa Group (Valencia, Spain) were used. All were whole grain flours except red lentil flour that came from dehulled lentils. The composition of the flours was determined in a previous study (Badia-Olmos et al., 2023). The properties of the raw flours, pastes, and gels of pulses were determined under different conditions: pH 3 ± 0.2 with and without added calcium, pH 5 ± 0.2 with and without added calcium, and compared to the natural conditions pH (6.3–7.1) and without calcium. The pH was adjusted using a 10% citric acid solution (Sensus, Valencia, Spain) with mineral water (Cortes, Spain). Calcium chloride 2-hydrate (CaCl2.2H2O) (PanReac, Barcelona, Spain) was added to the flour at 0.025 g Ca/g flour.

2.2. Water Holding Capacity

Three grams of flour were mixed with 30 mL of water. The solution was stirred in a vortex for 30 s, allowed to stand for 2 h at room temperature, and centrifuged using Centrifuge Sorvall RCS-B at 388 x g for 10 min at 20 °C. The supernatant was decanted and the tubes with sediment were weighed. Water holding capacity was calculated as g of water retained per g of flour (Aziah and Komathi, 2009). The experiment was repeated twice.

2.3. Emulsifying Capacity

One gram of flour, 20 mL of water, and 20 mL of sunflower oil were homogenized using an Ultraturrax (IKA T18 basic, Ultraturrax, Germany) at 9500 rpm for 1 min. The mixture was centrifuged at 3490 x g for 30 min at 20 °C (Centrifuge Sorvall Rcs-B) and then at 3000 x g for 5 min at 20 °C (Centrifuge 5810 R Eppendorf). Emulsifying Capacity (%) was calculated as the
volume of the emulsified layer/total volume after centrifugation in the centrifuge tube. The experiment was repeated twice.

2.4. Foaming Properties

One gram of flour was mixed with 50 mL of water. The solution was homogenized using an Ultraturrax (IKA T18 basic, Ultraturrax) at 13,500 rpm for 2 min and then transferred to a graduated cylinder using a spoon to recover all the foam. The foam volume was measured immediately to calculate the foaming capacity (increase in volume percentage due to foam) and after 30 min to calculate foaming stability. The experiment was repeated twice.

2.5. Pasting Behavior

Pasting behavior of the flours was determined using 7.5% flour in water. A starch paste cell adapted to a controlled stress rheometer (ARG2, TA Instruments, Cheshire, UK) with a Peltier concentric cylinder system to control the temperature was used. The mixture was placed in the cylindrical container and the viscosity values were recorded during the heating process, as the sample was stirred constantly at 160 rpm. The temperature was set at 50 °C for 1 min, then increased to 90 °C during 2.83 min, it was maintained at 90 °C for 5 min, and finally decreased to 50 °C. The experiment was repeated twice.

2.6. Viscoelastic Properties of Pastes

The pastes obtained in Sect. 2.5 were stored overnight at 4°C. Viscoelastic properties were measured using a controlled stress rheometer (RheoStress 1, Haake, Germany) equipped with a parallel plate geometry (60 mm diameter, 1 mm gap). The linear viscoelastic region of each sample was determined using preliminary stress sweep tests at 1 Hz and 20°C. Then, frequency sweep tests of 10 to 0.01 Hz were run at 20°C. The values of the storage modulus (G’), loss modulus (G’’), and loss angle tangent (tan δ), as a function of frequency, were registered. The experiment was repeated twice.

2.7. Texture Measurement of Gels

The gels were prepared with a kitchen robot (Thermomix, Vorwerk, Spain) in 500 g batches and using 15% flour in water. First, the mixture was homogenized at 1100 rpm for 2 min without applying temperature. Then it was heated for 20 min at 90 °C with stirring at 1100 rpm. Subsequently, the water evaporated during heating was recovered and the mixture was cooled for 5 min with gentle stirring at 100 rpm until it reached 65 °C. Finally, the paste was transferred to two glass containers (height = 37 mm, diameter = 65 mm), covered with plastic film and stored at
4 °C for 24 h. All textural measurements were made at 20 °C using a texture analyzer (TA/XT Plus, Stable Micro Systems Ltd., Surrey, UK).

2.7.1 Resistance to Penetration Using

Using a 10 mm diameter cylindrical probe, the force was registered when the sample gel in the cylindrical container (height = 37 mm, diameter = 65 mm) was penetrated to 5 mm at 1 mm/s. The maximum force value was obtained as a measure of the resistance to penetration. For each pulse and condition, two cylinders of two batches were measured.

2.7.2 Textural Profile Analysis

Texture Profile Analysis (TPA) was performed on gel cylinders (17 × 22 mm) using a 75-mm diameter flat aluminium disk (SMS P/75), and compressed twice (10%) at 1 mm/s. From the force-time curves, hardness (maximum force of the first compression) and springiness (distance ratio of the first to the second compression) were obtained. For each pulse and condition, eight cylinders were measured from two batches.

2.7.3 Compression up to Rupture of Gels

Gel cylinders (17 × 22 mm) were compressed at 1 mm/s up to 50% of their original height with a 75-mm diameter flat aluminium disk (SMS P/75). For each pulse and condition, eight cylinders were measured from two batches. The force and distance at rupture were obtained from the force-time curves to calculate the Young Modulus (E) (N/mm²) using formula 1:

$$E = \frac{F(h_0 - \Delta h)}{A_0 h_0 (ln(h_0 - \Delta h) - ln(h_0 - \Delta h))}$$

Where F is the rupture force, h0 and A0 are the original height and the surface of the sample. Δh is the distance at rupture (Bayarri et al., 2002).

2.8 Data Analysis

Analysis of Variance (ANOVA) of two factors (pulse and condition) with interaction was applied to each parameter studied. The Tukey test (α = 0.05) was used to calculate the significance of the differences among conditions for each pulse type. To summarize the differences among the type and conditions, principal component analysis (PCA) was applied to all parameters, including the properties of flours and its pastes and gels, considering the four pulse flours at the five conditions. All the analysis was conducted using XLSTAT 2021.4.1 software (Addinsoft, New York, USA).
3. RESULTS AND DISCUSSION

3.1. Properties of Pulse Flours at Different Conditions of pH and Calcium

ANOVA results showed that for all the flour properties (water holding, emulsifying, and foaming), values varied significantly ($\alpha = 0.05$) depending on the effects of pulse type, the condition (pH and Ca) and its interaction.

3.1.1. Water Holding Capacity

Table 8 presents the mean values of the water holding capacity of the four pulse flours under different conditions. The water holding capacity that corresponds to the amount of water retained per gram of flour ranged from 0.8 to 2.0 g/g. In natural conditions, the water holding capacity was the highest for white bean flour and the lowest for red lentil. Changes in water holding capacity with pH and added calcium depended on the flour. All flours showed higher water holding capacity at pH 3 than in natural condition, but in the presence of calcium, the increase was lower or values did not changed as it was the case of lentil and white bean flours. Furthermore, decreasing the pH to 5 increased the water holding capacity for red lentil and white bean flour only, and if calcium was not added. The water holding capacity of flours depend on the polysaccharides and proteins capable of adsorbing water, but also on the size of particles (Ettoumi, 2015; Pedrosa et al., 2020).

Du et al. (2014) observed a high-water holding capacity for legumes, explained mainly by the polysaccharide content. Berggren (2018) showed that it was mainly correlated with fiber content, although also modulated by other factors such as proteins, starch, and particle size. Similarly, in this study, the differences in water holding capacity among flour pulses are mainly explained by differences in fiber content (white bean (33.5%) > lentil (16.4%) > chickpea (14.0%) > red lentil (9.8%)). However, the effects of pH and calcium on the water holding capacity according to the literature seem more related to proteins and its solubility affected by pH and ionic strength (Patrascu et al., 2017). At a pH further away from the isoelectric point, the solubility is improved, preventing their aggregation and increasing the water holding capacity (Kumitch et al., 2020). Sreerama et al. (2012) described an isoelectric region between 4 and 6 for chickpea, cowpea, and horse gram legume flours, showing the solubility of proteins is higher at pH 2–3. This explains the higher water holding capacity observed at pH 3 for all flours. The presence of calcium however decreased water holding capacity probably due to the competition between the cations and protein for the water molecules, which enhances the protein-protein interactions and reduces its solubility.
Table 8. Mean values of the properties of pulse flours under different conditions (pH and calcium).

<table>
<thead>
<tr>
<th>Property</th>
<th>Condition</th>
<th>Chickpea</th>
<th>Lentil</th>
<th>Red Lentil</th>
<th>White Bean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Holding</td>
<td>Natural</td>
<td>1.1\textsuperscript{b}</td>
<td>1.5\textsuperscript{b}</td>
<td>0.8\textsuperscript{d}</td>
<td>1.7\textsuperscript{c}</td>
</tr>
<tr>
<td>Capacity (g/g)</td>
<td>pH5</td>
<td>1.1\textsuperscript{b}</td>
<td>1.6\textsuperscript{ab}</td>
<td>1.3\textsuperscript{b}</td>
<td>1.8\textsuperscript{b}</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>1.0\textsuperscript{b}</td>
<td>1.6\textsuperscript{b}</td>
<td>1.0\textsuperscript{c}</td>
<td>1.6\textsuperscript{d}</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>1.3\textsuperscript{a}</td>
<td>1.7\textsuperscript{a}</td>
<td>1.5\textsuperscript{a}</td>
<td>2.0\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>1.3\textsuperscript{a}</td>
<td>1.5\textsuperscript{b}</td>
<td>1.1\textsuperscript{bc}</td>
<td>1.6\textsuperscript{d}</td>
</tr>
<tr>
<td>Foaming Capacity (%)</td>
<td>Natural</td>
<td>53.1\textsuperscript{a}</td>
<td>72.6\textsuperscript{c}</td>
<td>61.2\textsuperscript{c}</td>
<td>50.7\textsuperscript{d}</td>
</tr>
<tr>
<td></td>
<td>pH5</td>
<td>48.9\textsuperscript{b}</td>
<td>68.8\textsuperscript{d}</td>
<td>60.3\textsuperscript{c}</td>
<td>52.5\textsuperscript{d}</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>50.5\textsuperscript{b}</td>
<td>74.4\textsuperscript{b}</td>
<td>68.6\textsuperscript{b}</td>
<td>74.6\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>44.3\textsuperscript{c}</td>
<td>78.7\textsuperscript{a}</td>
<td>68.6\textsuperscript{b}</td>
<td>62.7\textsuperscript{c}</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>50.4\textsuperscript{b}</td>
<td>78.8\textsuperscript{a}</td>
<td>72.6\textsuperscript{a}</td>
<td>68.1\textsuperscript{b}</td>
</tr>
<tr>
<td>Foaming Stability (%)</td>
<td>Natural</td>
<td>20.8\textsuperscript{e}</td>
<td>39.9\textsuperscript{e}</td>
<td>40.3\textsuperscript{d}</td>
<td>22.8\textsuperscript{e}</td>
</tr>
<tr>
<td>(30 min)</td>
<td>pH5</td>
<td>26.3\textsuperscript{d}</td>
<td>36.1\textsuperscript{d}</td>
<td>38.3\textsuperscript{c}</td>
<td>28.7\textsuperscript{d}</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>39.2\textsuperscript{b}</td>
<td>58.3\textsuperscript{a}</td>
<td>55.0\textsuperscript{b}</td>
<td>56.8\textsuperscript{b}</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>35.4\textsuperscript{c}</td>
<td>56.2\textsuperscript{b}</td>
<td>53.0\textsuperscript{c}</td>
<td>49.2\textsuperscript{c}</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>45.0\textsuperscript{a}</td>
<td>55.2\textsuperscript{b}</td>
<td>58.8\textsuperscript{a}</td>
<td>58.8\textsuperscript{a}</td>
</tr>
<tr>
<td>Emulsifying Capacity (%)</td>
<td>Natural</td>
<td>49.7\textsuperscript{a}</td>
<td>47.6\textsuperscript{a}</td>
<td>46.6\textsuperscript{a}</td>
<td>47.6\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td>pH5</td>
<td>5.4\textsuperscript{c}</td>
<td>3.7\textsuperscript{d}</td>
<td>2.9\textsuperscript{e}</td>
<td>4.4\textsuperscript{d}</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>7.1\textsuperscript{c}</td>
<td>6.7\textsuperscript{c}</td>
<td>13.4\textsuperscript{d}</td>
<td>10.1\textsuperscript{c}</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>7.9\textsuperscript{bc}</td>
<td>14.3\textsuperscript{b}</td>
<td>17.2\textsuperscript{c}</td>
<td>15.1\textsuperscript{b}</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>10.1\textsuperscript{b}</td>
<td>15.5\textsuperscript{b}</td>
<td>30.3\textsuperscript{b}</td>
<td>15.2\textsuperscript{b}</td>
</tr>
</tbody>
</table>

Note: For each flour, values that do not share letters indicate significant differences (α=0.05) according to Tukey’s test.

3.1.2. Emulsifying Capacity

Emulsifying capacity, measured as the amount of emulsion (% volume), varied greatly, with values ranging from 2.9 to 49.7%. All flours had a high emulsifying capacity under natural condition, being the highest for chickpea (49.9%) and the lowest for red lentil (46.6%). The emulsifying capacity of the four pulse flours decreased dramatically with a reduction in pH, but the effect was much higher at pH 5 than at pH 3. Emulsifying properties are usually attributed to proteins; however, in this case, the emulsion properties varied little between pulse flours. According to Pedrosa et al. (2020), emulsifying capacity depends highly on the protein content, especially the ratio of soluble proteins legumin/vecilin, and other factors such as the presence of carbohydrates. Polysaccharides, due to their hydrophilic character, often exhibit little surface activity at the oil–water interface and cannot act as emulsifiers. However, polysaccharides complexed with proteins can adsorb strongly at the oil–water interface and contribute to the formation and stabilization of emulsions. The electrostatic nature of these complexes make emulsions stabilized by protein-polysaccharide coacervates sensitive to pH and ionic strength.
Once the film is formed, the droplets can assume a negative or positive charge depending on whether the pH of the emulsion is above or below the protein’s isoelectric point. The high electrostatic repulsion between oil droplets leads to greater emulsion stability, whereas under pH conditions close to the protein’s isoelectric point droplet, flocculation/aggregation dominates, leading to coalescence and instability. At pH 3 and 5, the emulsifying capacity was enhanced by the presence of calcium which can be attributed to the electrostatic repulsion between oil droplets due to the ionic strength which stabilize the emulsion (Osemwota et al., 2021, Shevkani et al., 2019).

3.1.3. Foaming Capacity

The foaming capacity, corresponding to the increase in volume (%) due to foam formation, varied within the range of 44.3–78.8%. Foam stability (volume remaining after 30 min) ranged from 20.8 to 58.8% (Table 8). Lentil and red lentil flour produced more foam, and it was more stable over time than white bean and chickpea flours. The effect of conditions significantly (α = 0.05) affected both foaming parameters, but differences were more relevant in foaming stability. The effect of decreasing the pH depended on the presence of calcium. The foaming capacity and stability increased at pH 3 and increased further with added calcium. However, they decreased at pH 5 (without calcium), but when calcium was added, the values were similar or higher than under natural condition. For chickpeas, the variation in foaming capacity among conditions followed a different pattern, as it was higher under natural condition and slightly decreased at pH 3 and 5.

Proteins are especially relevant to foaming properties, as they are responsible for the formed interfacial film, which incorporate air bubbles in suspension and reduce the rate of coalescence (Aluko et al., 2009; Osemwota et al., 2021). Differences in foaming capacity and stability among flours under natural conditions are explained by the higher protein content in lentil and red lentil flours (24.0% and 25.9% respectively). Regarding changes with pH, the higher amount of foaming and stability observed at pH 3 and the lower values observed at pH 5 can be explained by the change in protein solubility. Proteins from pulses (bean, pea, and chickpea) showed higher foaming properties in the acidic condition (pH < 4) but lower values at a pH around the isoelectric point (4–6) (Shevkani et al., 2019). Calcium also played a relevant role in the foaming properties of pulses, and regardless of pH, calcium addition increased foaming properties. Previous studies showed improvement in the foaming properties of pulse flour with increased ionic strength (Farooq and
Boye, 2011), and of pulse proteins with the addition of calcium and magnesium (Ahmed et al., 2012), attributed to an increase in the solubility of proteins. However, other mechanisms such as calcium ion bridges forming between the carboxylic groups of proteins have been proposed that strengthen the interfacial film and thus improve the stability of foams (Miquelim et al., 2010).

3.1.4. Pasting Behavior of Pulses Flours at Different Conditions of pH and Calcium

The paste behavior curves of the pulse flour dispersions under different pH and calcium conditions are shown in Figure 10. In all cases, the viscosity of the flours remains constant during heating until the swelling point temperature when the viscosity suddenly increases due to gelatinization of starch. It reached a maximum value at 90 °C that remained almost constant when at 90 °C. Then, the viscosity values continuously increased during the cooling down period. It is noticeable that in these flours there is no decrease in viscosity during the heating period at 90 °C, indicating that starch in these flours is resistant to heating and shearing (Du et al., 2014). Li et al. (2014) reported that starch from legumes is resistant to swelling and rupture and display high pasting temperature.

Pasting temperature values ranged from 68.4 to 80.4 °C, maximum viscosity during heating; ranged between 84.0 and 268.0 mPa.s, and the viscosity at the end of the process ranged between 125.5 and 296.4 mPa.s (Table 9). ANOVA showed these three parameters varied significantly (α = 0.05) with the pulse type and the conditions (pH and calcium) and its interaction. In the natural condition, chickpea showed the highest viscosity values and lowest pasting temperature. The white bean showed the lowest viscosity values and the highest pasting temperature. The effect of pH and calcium on pasting parameters was similar for all flours except for white bean. Decreasing pH resulted in a decrease in pasting temperature and an increase in viscosity during the heating and cooling of chickpea, lentil, and red lentil flours; further- more, these effects were higher at pH 5, whereas they were higher at pH 3 for white bean flour. For lentil, red lentil, and chickpea flours, the effects of pH were lower when calcium was added, but higher for white bean flours. Pasting behavior of flours is mainly determined by starch, but other components, such as proteins, fibers, and lipids, should be considered (Adebowale & Adebowale, 2007).
Figure 10. Viscosity values during heating water dispersions of different pulse flours under different conditions of pH and calcium. For each flour, the two conditions that show extreme behaviors are presented.

In previous studies, the viscosity values of heated starch dispersions decreased with decreasing pH, which was attributed to the deterioration of the amorphous region of starch granules due to high acidity (Bravo-n et al., 2019; Joshi et al., 2014). Other studies indicate that acid modification changes the physicochemical properties of starch without destroying its granule structure and results in higher gelatinization temperature (Shi & Seib, 1992), higher solubility, gel strength, and lower viscosity (Kim & Ahn, 1996). However, here, the effect of pH on the viscosity profile was different and more complex depending on the pulse flour. For white bean flour, viscosity increased when the pH decreased. For lentil and red lentil flour, viscosity values were higher at pH 5 than under natural conditions and pH 3, indicating a possible effect of protein on the pasting behavior of starch. Natural and pH 3 conditions are far from the isoelectric point of proteins (4–6) which increases protein solubility and then decrease the availability of water for starch gelatinization.
Consequently, the process of starch gelatinization may be delayed, resulting in a higher pasting temperature and lower viscosity. Likewise, the decrease in viscosity with calcium can be explained by the availability of water. Torres et al. (2014) reported that the presence of salts lowers water activity, delaying and limiting starch gelatinization.

Table 9. Mean values of Pasting Behavior parameters of pulse flours at different conditions (pH and calcium).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Chickpea</th>
<th>Lentil</th>
<th>Red Lentil</th>
<th>White Bean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pasting Temperature (°C)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>73.3 b</td>
<td>73.1 a</td>
<td>73.3 a</td>
<td>80.4 a</td>
</tr>
<tr>
<td>pH5</td>
<td>70.6 c</td>
<td>68.4 c</td>
<td>71.0 b</td>
<td>78.2 b</td>
</tr>
<tr>
<td>pH5Ca</td>
<td>73.4 b</td>
<td>70.8 b</td>
<td>73.2 a</td>
<td>77.4 bc</td>
</tr>
<tr>
<td>pH3</td>
<td>73.3 b</td>
<td>70.8 b</td>
<td>73.2 c</td>
<td>75.8 c</td>
</tr>
<tr>
<td>pH3Ca</td>
<td>75.8 a</td>
<td>73.1 a</td>
<td>72.9 a</td>
<td>75.7 c</td>
</tr>
<tr>
<td><strong>Maximum Viscosity during heating at 90 °C (mPa.s)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>178.3 bc</td>
<td>84.0 b</td>
<td>94.0 d</td>
<td>44.4 b</td>
</tr>
<tr>
<td>pH5</td>
<td>268.0 a</td>
<td>177.7 a</td>
<td>229.0 a</td>
<td>60.5 b</td>
</tr>
<tr>
<td>pH5Ca</td>
<td>178.3 bc</td>
<td>175.1 a</td>
<td>198.8 ab</td>
<td>102.8 a</td>
</tr>
<tr>
<td>pH3</td>
<td>207.9 ab</td>
<td>141.1 ab</td>
<td>175.6 bc</td>
<td>128.2 a</td>
</tr>
<tr>
<td>pH3Ca</td>
<td>120.5 c</td>
<td>111.1 ab</td>
<td>142.8 c</td>
<td>115.7 a</td>
</tr>
<tr>
<td><strong>Viscosity at the end of the process 50 °C (mPa.s)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>256.4 a</td>
<td>125.5 c</td>
<td>137.7 b</td>
<td>74.8 e</td>
</tr>
<tr>
<td>pH5</td>
<td>296.4 a</td>
<td>204.2 ab</td>
<td>261.4 a</td>
<td>85.1 c</td>
</tr>
<tr>
<td>pH5Ca</td>
<td>242.1 a</td>
<td>217.4 a</td>
<td>259.3 a</td>
<td>170.5 b</td>
</tr>
<tr>
<td>pH3</td>
<td>262.4 a</td>
<td>192.1 ab</td>
<td>247.7 a</td>
<td>172.0 b</td>
</tr>
<tr>
<td>pH3Ca</td>
<td>160.1 b</td>
<td>152.6 bc</td>
<td>193.2 ab</td>
<td>313.2 a</td>
</tr>
</tbody>
</table>

Note: For each flour and parameter, values that do not share letters indicate significant differences (α = 0.05) according to Tukey’s test.

3.1.5. Rheological Properties of Pulse Pastes Under Different pH and Calcium Conditions

All flour pastes (Figure 11) showed a similar viscoelastic response typical of gel materials, with G’ values higher than G’’ and slightly dependent on frequency. Values of G’, G’’, tan δ at a frequency of 1 Hz were used to compare viscoelastic properties (Table 10). ANOVA showed that viscoelastic parameters varied significantly (α = 0.05) with the pulse type and the conditions (pH and calcium), and their interaction. Under natural condition, chickpea paste had the highest values of G’ and G’’, white bean paste had the lowest values of G’ and G’’, and the highest tan δ. For chickpea, lentil and red lentil pastes, the values of G’ and G’’ significantly (α = 0.05) increased when decreasing pH to 5 with and without calcium, but when decreasing pH to 3, the increase in G’ and G’’ was lower or not significant compared to the natural condition. For white bean paste, decreasing pH with or without calcium, increased G’ and G’’ and lowered tan δ, this effect was
higher at pH 3 with calcium. The variation in the rheological behavior of pastes depends highly on starch content (Farooq & Boye, 2011; Pang et al., 2020).

During cooling, starches change their structure, become more ordered, and form a network. In our study, the results varied depending on the type of pulse. Chickpea, lentil, and red lentil pastes had higher $G'$ and $G''$ and lower tan δ reflecting a typical gel structure. However, white bean paste had higher values when lowering pH. Motta & Zhang (2019) suggested that other non-starch components of bean flours, like proteins, could affect their rheological behavior, as they can form a matrix when heated. In acidic conditions, Kaur & Singh (1999) reported that changes in wheat paste are attributed to changes on the proteins. Furthermore, the increase in the storage modulus of starch gels with the content of protein at pH 5 was related to increased aggregation and denaturation during thermal treatment (Van Kleef, 1986; Shim & Mulvaney, 2001; Xu et al., 2015). At pH close to their isoelectric point, proteins aggregate and result in network formation due to their low solubility (Manassero et al., 2018). This could explain the higher values of $G'$ and $G''$ of lentil, red lentil, and chick-pea pastes obtained at pH 5 with a gel form. The different behavior of the white bean paste that showed an increase in the storage and loss modulus at pH 3 could be explained by the effect of the type of proteins and other components of each pulse on their viscoelastic properties.
Figure 11. Mechanical spectra of pulse flour pastes obtained under different pH and Calcium conditions. For each flour, the pastes with extreme behaviours are presented. Paste under natural conditions (○), paste at pH 5 without calcium (Δ), paste at pH 3 without calcium (□), paste at pH 3 with calcium (◊). G’ (filled symbols) and G” (open symbols).
Table 10. Mean values of $G'$ and $G''$ and tan $\delta$ (at 1 Hz) of pulse pastes under different conditions (pH and calcium).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Chickpea</th>
<th>Lentil</th>
<th>Red Lentil</th>
<th>White Bean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G'$ (Pa)</td>
<td>Natural</td>
<td>586.7$^b$</td>
<td>233.4$^c$</td>
<td>436.4$^b$</td>
<td>21.0$^d$</td>
</tr>
<tr>
<td></td>
<td>pH5</td>
<td>898.2$^a$</td>
<td>1267$^a$</td>
<td>1646.0$^a$</td>
<td>164.0$^c$</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>869.4$^a$</td>
<td>1089.5$^a$</td>
<td>1613.5$^a$</td>
<td>134.4$^c$</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>484.8$^b$</td>
<td>679.9$^b$</td>
<td>474.9$^b$</td>
<td>416.3$^b$</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>580.0$^b$</td>
<td>411.1$^bc$</td>
<td>342.3$^b$</td>
<td>663.4$^a$</td>
</tr>
<tr>
<td>$G''$ (Pa)</td>
<td>Natural</td>
<td>65.1$^b$</td>
<td>21.7$^c$</td>
<td>31.9$^c$</td>
<td>5.5$^d$</td>
</tr>
<tr>
<td></td>
<td>pH5</td>
<td>105.9$^a$</td>
<td>155.4$^a$</td>
<td>179.3$^a$</td>
<td>24.3$^c$</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>115.1$^a$</td>
<td>157.8$^a$</td>
<td>155.9$^a$</td>
<td>20.9$^{cd}$</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>65.4$^b$</td>
<td>114.9$^{ab}$</td>
<td>74.0$^b$</td>
<td>48.0$^b$</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>87.5$^{ab}$</td>
<td>63.6$^{bc}$</td>
<td>43.7$^{bc}$</td>
<td>107.0$^a$</td>
</tr>
<tr>
<td>tan $\delta$ (G''/G')</td>
<td>Natural</td>
<td>0.11$^b$</td>
<td>0.09$^b$</td>
<td>0.07$^c$</td>
<td>0.26$^c$</td>
</tr>
<tr>
<td></td>
<td>pH5</td>
<td>0.12$^{ab}$</td>
<td>0.12$^{ab}$</td>
<td>0.11$^b$</td>
<td>0.15$^{bc}$</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>0.13$^{ab}$</td>
<td>0.14$^{ab}$</td>
<td>0.10$^{bc}$</td>
<td>0.16$^{bc}$</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>0.13$^{ab}$</td>
<td>0.17$^a$</td>
<td>0.16$^a$</td>
<td>0.12$^c$</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>0.15$^a$</td>
<td>0.16$^{ab}$</td>
<td>0.13$^{ab}$</td>
<td>0.16$^b$</td>
</tr>
</tbody>
</table>

Note: For each flour and parameter, values that do not share letters indicate significant differences ($\alpha = 0.05$) according to Tukey’s test.

3.1.6. Mechanical Properties of Pulse Gels at Different Conditions of pH and Calcium

The four pulses at a concentration of 15% (w/w) formed gels, and the values of the maximum force at penetration, hardness, and springiness were obtained (Table 11). ANOVA showed that they varied significantly ($\alpha = 0.05$) with pulse type and conditions (pH and calcium) and its interaction. Important variations among gels were observed for the maximum force at penetration (1.30–4.64 N) and hardness (0.50–2.25 N). Under natural conditions, red lentil gel showed the highest values of both parameters, whereas white bean gel showed the lowest. Both the maximum force at penetration and the hardness values changed with pH and calcium, except for the white bean gel that did not show significant differences between the gels prepared under different conditions. For the other three pulses, decreasing pH and adding calcium resulted in less hard and less resistant gels. Both parameters were lower at pH 3 than at pH 5 except for chickpea, which showed little differences between gels prepared at pH 5 and pH 3. The springiness values of the pulse flour gels were high (> 0.65) except for white beans that showed poor ability to recover shape. The springiness slightly changed with the conditions.
Table 11. Mean values of mechanical properties of pulse gels under different conditions (pH and calcium).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Chickpea</th>
<th>Lentil</th>
<th>Red Lentil</th>
<th>White Bean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Force at penetration (N)</td>
<td>Natural</td>
<td>3.36a</td>
<td>3.44a</td>
<td>4.64a</td>
<td>1.26NS</td>
</tr>
<tr>
<td></td>
<td>pH5</td>
<td>2.88ab</td>
<td>3.50a</td>
<td>4.62a</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>2.01b</td>
<td>2.23ab</td>
<td>4.48a</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>1.86b</td>
<td>0.76b</td>
<td>2.32b</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>1.77b</td>
<td>1.07b</td>
<td>2.16b</td>
<td>1.30</td>
</tr>
<tr>
<td>Hardness (N)</td>
<td>Natural</td>
<td>1.02a</td>
<td>1.23ab</td>
<td>2.25a</td>
<td>0.67NS</td>
</tr>
<tr>
<td></td>
<td>pH5</td>
<td>0.98a</td>
<td>1.65a</td>
<td>2.00a</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>0.55b</td>
<td>1.07b</td>
<td>2.11a</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>0.90c</td>
<td>0.43c</td>
<td>0.96b</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>0.89c</td>
<td>0.48c</td>
<td>0.97b</td>
<td>0.50</td>
</tr>
<tr>
<td>Springiness</td>
<td>Natural</td>
<td>0.82a</td>
<td>0.82a</td>
<td>0.88a</td>
<td>0.44NS</td>
</tr>
<tr>
<td></td>
<td>pH5</td>
<td>0.82a</td>
<td>0.82ab</td>
<td>0.82ab</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>pH5Ca</td>
<td>0.72b</td>
<td>0.80ab</td>
<td>0.90a</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>pH3</td>
<td>0.81ab</td>
<td>0.65b</td>
<td>0.76b</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>pH3Ca</td>
<td>0.82a</td>
<td>0.72ab</td>
<td>0.81ab</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Note: For each flour and parameter, values that do not share letters indicate significant differences (α = 0.05) according to Tukey’s test. N.S: no significant difference.

Young modulus was lower for white bean gel and higher for red lentil (Figure 12). For lentil and red lentil gels, Young’s modulus decreased when decreasing the pH to 3 and for chickpea gel, it decreased with calcium addition. The mechanical properties depend on the structure, swollen starch granules and proteins in the continuous phase that can form a network. In the literature, the effect of lowering the pH in starch gels is different between papers, but in most cases, the reduction in pH resulted in stiffer gels. In corn starch, the addition of citric acid hydrolyzed amylose and amylopectin that resulted in a higher retrogradation and gel strength at pH 3 and pH 5 than under natural conditions (Jiménez et al., 2016). Another explanation could be the effect of pH on the gelation of protein. Renkema et al. (2002) studied the influence of pH and ionic strength on gel formation and gel properties of soy protein isolates (SPI) in relation to denaturation and protein aggregation/precipitation. The results showed that the stiffness of the gel increased with the decrease in pH due to a different gelation mechanism.

At pH 3.8, the proteins aggregate to a greater extent, resulting in coarser gels with low stiffness, whereas at pH 7.6 the proteins were less aggregated, resulting in more fine-strand gels. Moreover, (Salinas et al., 2012) studied the effect of calcium addition on the rheological properties of wheat...
flour which resulted in a stiffer dough. The authors attributed this behavior to the development of three-dimensional network due to the bridges formed among the negatively charged proteins enhanced by calcium presence.

**Figure 12.** Mean values of Young Modulus $E$ (N/mm$^2$) obtained from compression at rupture test of pulse flour gels under different conditions (pH and calcium). For each flour, the letters on the top of the bars indicate significant differences ($\alpha = 0.05$) between the mean values according to the Tukey test. N.S: no significant difference.

PCA was used to summarize changes in the properties of pulses under different conditions. **Figure 13** shows the first plot of the two components that explained the 67.63% of the total variance. The first component was positively correlated with the hardness, elasticity, and the stiffness of the gels and viscosity and viscoelastic parameters ($G'$ and $G''$) of pastes and negatively correlated with the water holding capacity and pasting temperature. The second component was positively correlated with the emulsifying capacity and negatively correlated with the foaming capacity and stability. The flours and conditions that can be used for favoring certain properties can be easily obtained from this plot. Hard, stiff, and elastic gels can be obtained from red lentil and chickpea flours, whereas white bean gels are soft and more plastic. High viscosity pastes with high values of viscoelastic moduli are obtained from red lentil, chickpea, and lentil flours at pH 5, whereas low-viscosity pastes are obtained from white bean flour, which also provided more water holding capacity. The four pulses provide maximum emulsifying capacity under natural conditions.
4. CONCLUSION

The four pulse flours (chickpea, lentil, red lentil and white bean) exhibit different techno-functional properties that also varied with the conditions of pH and ionic strength, providing a wide range of possibilities to modulate the structure and texture of new or alternative plant-based products. The four pulse flours are good emulsifiers at natural conditions, which is a desirable feature in the development of different food categories such as baby food, bakery products and soups. When heated in water, pulse flours can form viscous pastes or gels depending on the concentration (10% and 15%, respectively). Chickpea flour provides higher viscosity in pastes and the red lentil the stiffer gel. These findings make them suitable choice for bakery and snack food, soups, cheese analogues and cold-set product in terms of texture properties.

The water holding capacity, foaming capacity and viscosity can be improved by decreasing the pH. However, the emulsifying capacity and gel hardness and stiffness are not improved but decrease at low pH (especially at 3). This should be taken into consideration when designing the texture of new food products based on pulse flours.

Figure 13. Principal component analysis of the techno-functional properties of pulse flours and their pastes and gels under different conditions (pH and calcium).
5. ACKNOWLEDGEMENTS
The authors are grateful to the Dacsa group (Valencia, Spain) for providing pulse flours used in this study. Thanks to Spanish government MCIN/AEI to the Center of Excellence Accreditation Severo Ochoa (CEX2021-001189-S/ MCIN/AEI / https://doi.org/10.13039/501100011033).

The authors also acknowledge the Algerian government for the scholarship offered to Djemaa Moussaoui giving an opportunity to perform this study.
3.2. STUDY 2

Mechanical and Sensory Properties of Pulse Gels in the Development of New Plant Based Food

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*Sustainability* 2023, *15*, 9407.

DOI: 10.3390/su15129407
Mechanical and Sensory Properties of Pulse Gels in the Development of New Plant Based Food

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KEYWORDS

Plant-based; natural ingredients; vegetal protein; texture; flavour; Flash Profil
ABSTRACT

The shift towards healthier and sustainable food consumption requires a greater variety of plant-based products. This study aimed to determine how the mechanical and sensory properties of three different pulse gels (chickpea, lentil, or red lentil flour) vary with the ingredients (flour, oil, lemon, and salt content). All pulse flours were able to form self-standing gels. Mechanical properties varied with the pulse type and with the formulation differently depending on the pulse. For all pulses, the hardness and stiffness increased with the flour content and decreased with salt. They decreased with lemon in chickpea gels and increased with oil content in the red lentil gel. The Flash Profile technique provided distinctive sensory characteristics of each pulse gel. The red lentil gels were homogeneous, creamy, and compact. The chickpea gels were also compact, but harder. Lentil flour resulted in rough and sandy gels. For the three pulses, including oil and lemon reduced pulse flavors and increased sour taste. The results of this study give insights into the suitability of pulse gels to be the basis of new solid plant-based products whose sensory properties can be modulated by varying the concentration of natural ingredients.
1. INTRODUCTION

In recent years, due to consumers’ awareness about health and environmental problems issued from animal-based food consumption, there is an increasing interest in plant-based food (Argel et al., 2020; Tarrega et al., 2020). It was reported that about 75 million consumers around Europe purchase vegetarian or vegan food products (Gebhardt, 2020). Most plant-based products on the market are analogues that try to mimic meat or dairy products; therefore, most research is devoted to the challenge of emulating their properties (Jeske et al., 2018; Sharma et al., 2023). However, an increase in the availability and variety of plant-based products is necessary to convince consumers (Alcorta et al., 2021; Aschemann-Witzel et al., 2020), so other innovation strategies need to be considered when placing new products in the plant-based market. Still, it should be considered that the expected increase in the demand for plant-based products is mainly driven by flexitarians who seek to reduce their consumption of animal products without cutting them out. These consumers are less interested in “imitation” alternatives of products they already eat, and when seeking plant-based products, they may prefer other product concepts or recipes that they could enjoy and incorporate into the diet (Alcorta et al., 2021; Dagevos, 2021). In addition, most plant-based products in the current market are made from soy or gluten (Amar & Surono, 2013; N Grasso et al., 2021; Jeske et al., 2018; Matias et al., 2014), and the list of ingredients usually contains many additives (stabilizers, emulsifiers, acidifiers, salt, colorings, flavorings, and preservatives) that help overcome limitations in tech-no-functional properties of the plant-based ingredients (Jeske et al., 2018), but it is one of the main drawbacks for consumers who perceive them as not natural or too processed.

Pulses are also a source of vegetal proteins and can be considered a good alternative to wheat and soy, taking into account their low allergenicity; therefore, they are safe for numerous consumers (Guldiken et al., 2022; Tarrega et al., 2020). Regarding sustainability, pulses can fix atmospheric nitrogen, thus reducing the amount of fertilizer used in crops (Anne Saint-Eve, Pablo Granda, Guillaume Legay, Gérard Cuvelier, 2019; Proserpio et al., 2020). Pulses have a high content of protein (17% to 30%), carbohydrates, essential vitamins, and minerals and are low in fat (Ferawati et al., 2019; Shevkani et al., 2019). Moreover, pulse proteins provide a high content of amino acids such as lysine, among others, and they are rich in bioactive compounds. In addition, pulse proteins exhibit high digestibility, resulting in higher absorption of the macronutrient by the human body.
Thus, pulse proteins could be considered as a great choice for consumers seeking dense nutrient options and rich protein products (Jahreis et al., 2016).

From a technological viewpoint, some pulse flours such as lentil, red lentil, and chickpea can also form strong gels that can be the basis of solid products (Badia-Olmos et al., 2023; Diaz et al., 2019; Ettoumi & Chibane, 2015; M. Kaur & Singh, 2005; Tas et al., 2022). Gels are mainly based on the formation of a three-dimensional network of a starch–protein matrix. Gelation properties of flours depend on the relative ratio of different constituents such as proteins, lipids, and carbohydrates (Aguilera et al., 2009). Previous studies showed that the techno-functional properties of pulse gels depend on flour concentration and conditions such as pH and ionic strength, as well as on the effect of heating treatment (Renkema et al., 2002; Ettoumi et al., 2016; Moussaoui et al., 2023; Shevkani et al., 2021a). Most studies dealing with technological properties of pulse flours (Ettoumi & Chibane, 2015; Patrascu et al., 2017) aimed to include flours in the formulation of conventional products as a way of enrich them in protein with, in general, little attention to sensory properties (Boukid et al., 2019). However, the approach of using different pulse flours as the base for creating new products has been only scarcely explored.

To respond to the consumer’s demand for more variety of plant-based products, our hypothesis is that the use of pulse flours and the inclusion of natural ingredients such as lemon juice, oil, and salt can be a successful strategy in creating different new solid plant-based products whose sensory properties can be modulated by changing the amount of ingredients. From a practical viewpoint, the knowledge on how changes in the formulation influence the properties of a product is needed in the development of products. Mechanical properties are of special relevance in the elaboration of solid-formulated products because they provide identity to the product, and they are usually quality indexes closely related to the sensations of texture that the product will provide. The mechanical properties depend largely on the structure of the product. The measurement of mechanical properties is based on evaluating the response to deformation (compression, shear, or penetration) that is adapted depending on the product and how it is consumed. Regarding sensory properties, Flash Profile is one of the rapid sensory techniques proven to be useful for describing and quantifying sensory differences among products (Dairou & Sieffermann, 2002; Lassoued et al., 2008). Since participants generate and individually use their own attributes, it is especially useful for exploring the terms that describe characteristics of a new concept product. Since it is
based on the evaluation of differences in the intensity of the attributes, it is also ideal for being used when evaluating changes in the content of ingredients (Tarrega et al., 2017).

The aim of this work was to determine the variations in mechanical and sensory properties of pulse gels (lentil, red lentil, or chickpea) with the content of flour, lemon juice, oil, and salt and to know how they can be modulated to develop new solid plant-based products composed of natural ingredients.

2. MATERIALS AND METHODS

In this study, lentil, red lentil, and chickpea pulse flours were used. All were whole grain flours except red lentil flour, which came from dehulled lentils. The flours were provided by Molendum Ingredientes (Zamora, Spain) and stored at 4 °C. Mineral water (Cortes, Spain), salt (Hacendado, Spain), sunflower oil (Hacendado, Spain), and lemon juice (Hacendado, Spain) were also used to prepare the gels.

2.1 Gels Composition and Preparation

The effect of varying the concentration of four ingredients (flour, oil, lemon, and salt) on the mechanical properties of pulse gels was investigated. For this, gels were prepared varying the concentration of each ingredient in the following ranges: flour (15% to 17.5%), oil (0% to 2.8%), lemon (0% to 2.8%), and salt (1% to 1.4%). The 17 formulations studied (Table 12) followed the fractional factorial design (2^4) with augmentation (addition of axial and center points) proposed by Gacula et al. (1993) to estimate both simple and quadratic effects, and binary interactions of the factors studied

\[
Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_{14}X_1X_4 + B_{24}X_2X_4 + B_{34}X_3X_4 + B_{11}X_1^2 + B_{22}X_2^2 + B_{33}X_3^2 + B_{44}X_4^2 + \text{Error}
\]

where Y is the variable studied, B_0 is the intercept (constant), B_1, B_2, B_3, B_4 are the linear coefficients, B_{11}, B_{22}, B_{33}, B_{44} are the quadratic coefficients, B_{14}, B_{24}, B_{34}, B_{44} the interaction effects, and X_1, X_2, X_3, X_4 are the independent variables for flour concentrations, oil, lemon, and salt, respectively.

The gels were prepared with a kitchen robot (Mambo 9090, Cecotec, Spain) in 600 g batches. The ingredients were mixed for 2 min and subsequently heated at 90 °C for 8 min while stirring, and then cooled for 6 min. The mixture was transferred to two cylindrical glass containers (height = 36
mm, diameter = 62 mm), covered with plastic film, and stored at 4 °C for 24 h. Two batches per formulation were prepared.

**Table 12.** Experimental design and composition of pulse gels used in the study of the mechanical properties.

<table>
<thead>
<tr>
<th>Formulation</th>
<th>Flour %</th>
<th>Oil %</th>
<th>Lemon %</th>
<th>Salt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.4</td>
<td>0.4</td>
<td>0.4</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>15.4</td>
<td>2.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>15.4</td>
<td>0.4</td>
<td>2.4</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>15.4</td>
<td>2.4</td>
<td>2.4</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>17.1</td>
<td>0.4</td>
<td>0.4</td>
<td>1.2</td>
</tr>
<tr>
<td>6</td>
<td>17.1</td>
<td>2.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>17.1</td>
<td>0.4</td>
<td>2.4</td>
<td>0.2</td>
</tr>
<tr>
<td>8</td>
<td>17.1</td>
<td>2.4</td>
<td>2.4</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>16.25</td>
<td>1.4</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>10</td>
<td>16.25</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>11</td>
<td>16.25</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>12</td>
<td>16.25</td>
<td>0</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>13</td>
<td>16.25</td>
<td>2.8</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>14</td>
<td>16.25</td>
<td>1.4</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>15</td>
<td>16.25</td>
<td>1.4</td>
<td>2.8</td>
<td>0.7</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>1.4</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>17</td>
<td>17.5</td>
<td>1.4</td>
<td>1.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>
2.2 Mechanical Properties of Pulse Gels

Textural measurements of gels (texture profile analysis, compression up to rupture, resistance to penetration, and cutting test) were conducted using a texture analyzer (TA/XT Plus, Stable Micro Systems Ltd., Surrey, UK).

2.2.1 Texture Profile Analysis

Texture profile analysis was performed on gel cylinders (height = 22 mm, diameter = 17 mm) using an aluminum probe with a diameter of 75 mm (SMS P/75). Force was registered while the gel cylinder was compressed twice, up to 10% of its original height and at a constant speed of 1 mm/s. From the force–time curves, mechanical parameters were obtained. Hardness was obtained as the maximum force achieved during the first compression cycle. Cohesiveness was obtained as the relative resistance to deformation between the 2 cycles of compression (Area 2/Area 1), excluding the areas under the decompression portion. Gumminess was obtained as the product of hardness and cohesiveness. Measurements were conducted twice, and eight cylinders of two batches were analyzed.

2.2.2 Compression up to Rupture

Gel cylinders (height = 22 mm, diameter = 17 mm) were compressed at 1 mm/s up to 75% of their original height with a 75 mm diameter flat aluminum disk (SMS P/75). Measurements were conducted twice, and eight cylinders from two batches were analyzed. The force and distance at rupture were obtained from the force–time curves to calculate Young’s modulus (N/mm²) using the following formula:

\[
\text{Young Modulus} = \frac{F(h_0 - \Delta h)}{A_0 \ln(h_0 - \ln(h_0 - \Delta h))}
\]

where F is the rupture force, h₀ and A₀ are the original height and the surface of the sample, respectively, and Δh is the distance at rupture (Bayarri et al., 2002).

2.2.3 Resistance to Penetration

The penetration test was conducted using a 10 mm diameter cylindrical probe. The force was recorded when the sample gel contained in the cylindrical container (height = 62 mm, diameter = 36 mm) was penetrated to 5 mm at 1 mm/s. The value of the area under the curve was obtained to
show the resistance to penetration. Measurements were conducted twice, and two cylinders per batch were measured.

2.2.4 Cutting Test

Gel cylinders (height = 62 mm, diameter = 36 mm) were cut transversally at 100% at a constant speed of 1 mm/s using a butter/wire cutter (A/BC). From the force–time curves, the cutting force expressed as the maximum force required to cut the sample at 100% was obtained. Measurements were conducted twice and two cylinders per batch were measured.

2.3 Sensory Evaluation

2.3.1 Composition and Preparation of Gels

For each pulse flour (Lentil: LF, Chickpea: CF, Red Lentil, RF), six formulations were considered that varied in the amount of flour (low or high) and in the presence of the other two ingredients, oil (O) or oil and lemon (O + L). The salt concentration used (0.7%) was kept constant across samples and evaluations.

The gels for sensory evaluation were prepared as described in Section 2.2, transferred to a plastic container (length = 150 mm, width = 105 mm, height = 20 mm), covered with plastic film and stored at 4 °C for 24 h. Before sensory evaluation, the gels were cut into cubes (length = 2.5 cm, width = 0.8 cm, height = 1.5 cm), labeled with three-digit random codes, and served at 20 °C.

2.3.2 Procedure

Nineteen participants (fourteen women and five men) with previous experience in sensory evaluation evaluated the pulse gels. The Flash Profile method was used to evaluate the sensory differences among pulse gels. A first session was used to generate the list of terms of each participant through an individual interview. Each participant was asked to indicate the terms that described the differences and similarities among the three pairs of gel samples. The individual list of attributes (appearance, texture, and flavor) was collected for each assessor. The sensory evaluation of the gels was conducted over four different sessions. In three separate sessions (one per pulse flour), the sensory differences among the six gels produced with the same pulse flour but different formulation (flour, oil, and lemon content; Table 13) were evaluated. In a fourth session, gels of different pulses were compared using two gels of each pulse. The formulation of the two gels included a high amount of flour (17.4%), one without oil and lemon and the other one with
both ingredients (Table 13). In each session, participants evaluated sensory differences using ranking tests using their own list of attributes. Six samples were presented simultaneously to the participants, who were asked to rank the samples from low to high intensity for each attribute (ties were allowed). Water was provided to the participants to rinse their mouths. The procedure was approved by the Ethics Committee of CSIC (resolution number 199/2020). Participants gave their informed consent before participating in the study.

Table 13. Formulation of pulse flour gels included in the different sensory evaluation sessions.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Chickpea Flour (Session 2)</th>
<th>Red Lentil Flour (Session 3)</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF-Low</td>
<td>CF-Low</td>
<td>RF-Low</td>
<td>Flour (%)</td>
</tr>
<tr>
<td>LF-Low + O</td>
<td>CF-Low + O</td>
<td>RF-Low +O</td>
<td>15.1</td>
</tr>
<tr>
<td>LF-Low + O + L</td>
<td>CF-Low + O + L</td>
<td>RF-Low+O+L</td>
<td>15.1</td>
</tr>
<tr>
<td>LF-High *</td>
<td>CF-High *</td>
<td>RF-High *</td>
<td>17.4</td>
</tr>
<tr>
<td>LF-High + O</td>
<td>CF-High + O</td>
<td>RF-High + O</td>
<td>17.4</td>
</tr>
<tr>
<td>LF-High+ O + L*</td>
<td>CF-High + O + L*</td>
<td>RF-High + O + L *</td>
<td>17.4</td>
</tr>
</tbody>
</table>

* Samples included in the session 4.

2.4 Data Analysis

Analysis of variance (ANOVA) of two factors (flour type and formulation) with interaction was applied to the data of the mechanical parameters of gels (hardness, gumminess, Young’s modulus, area of penetration, and cutting force). For each mechanical property, the model explaining its variation with the formulation (flour, lemon, oil, and salt) was established using a nonlinear stepwise regression (probability for entry and removal equal to 0.05). Response surface plots were used to visualize the variation of mechanical properties with the formulation in those models that were complex. Generalized Procrustes Analysis (GPA) was performed on the Flash Profile ranking data to generate the factorial map representing sensory differences among samples. The analyses were performed using XLSTAT version 2020.4.1 software (Addinsoft, New York, NY, USA). The response surface plots were performed using MATLAB version 2023.02 (Mathworks, Natick, CA, USA).
3. RESULTS AND DISCUSSION

3.1 Mechanical Properties of Pulse Gels

Pulse flour dispersions in water subjected to heating created self-standing gels in all the formulations studied. The mechanical properties of the gels were characterized under different deformations: compression (hardness, gumminess, and Young’s modulus), shear (cutting force), and penetration (penetration area). Figure 14 shows the average values of each mechanical property for each pulse and formulation. ANOVA showed that the three parameters obtained from the compression tests varied depending on the type of flour (p < 0.001), the formulation (p < 0.001), and its interaction (p = 0.021 for hardness, p = 0.025 for gumminess, and p < 0.001 for Young’s modulus).

Hardness and gumminess values were higher for red lentil gels and lower for chickpea gels. Young’s modulus, which indicates the stiffness of the gel, was higher for red lentil gels and lower for lentil ones. However, as indicated by the interaction effect observed for the three parameters, the differences among pulses depended on the formulation, indicating that variations in the composition (lemon, oil, salt, and flour contents) affected the three pulses differently. Like the compression parameters, the values of the penetration area and cutting force varied depending on the type of flour (p < 0.001), the formulation (p < 0.001), and the interaction (p < 0.001). For the penetration area, which indicates the resistance of gels to penetration (Laguna et al., 2014), the values were higher for red lentil and lower for chickpea 7.32–13.67 and 4.92–10.86 N/s, respectively. Furthermore, the cutting force revealed that the differences among pulses were lower and highly dependent on the formulation. The effect of each ingredient (flour, oil, lemon, and salt) and their interactions on the mechanical properties of pulse gels was studied by regression analysis.

Table 14 shows for each pulse the equation of the regression model relating each mechanical parameter with the formulation variables. Equations included the terms that significantly affected the values of the mechanical parameter (p < 0.05). The terms included in the model were different among pulses, which confirms that variations on formulation affected the mechanical properties of gels differently. For hardness and gumminess, the models included the same terms, indicating that they presented a similar variation with formulation. For lentil, the equations included a positive quadratic relation with flour and a negative linear relationship with salt, so hardness and
gumminess increased when the flour concentration increased (from 15% to 17.5%) and decreased as the salt increased (0% to 1.4%).

With red lentil, the equations were more complex and included quadratic effects of flour and salt (positive) and oil (negative) and the interaction effects between salt and flour (negative) and between oil and flour (positive). As observed in Supplementary Figure S1, hardness and gumminess increased with the flour content, but the increase was greater at low levels of salt and at high levels of oil. The values increased with increasing oil content to a maximum point of 2% oil, from which they started to decrease slightly. The values decreased with salt content until a minimum value at 1% salt from which they increased slightly. Therefore, the maximum values of hardness and gumminess using red lentil can be obtained using low levels of salt (approximately 0%), intermediate levels of oil (1.4%), and high levels of flour (17.5%). For chickpea, hardness and gumminess were affected by flour (positive), lemon (negative), and the salt and flour interaction (negative) as shown in Supplementary Figure S2. Values increased with the flour content and decreased slightly with the lemon content. The effect of flour depended on the salt concentration, as reflected by the negative interaction between salt and flour. At higher levels of salt, the increase in hardness and gumminess with flour concentration was slightly lower. The maximum values of hardness and gumminess in chickpea gels are obtained using low levels of salt and lemon and high levels of flour.

Young’s modulus of all pulse gels increased with flour concentration. For lentil, Young’s modulus also depended on salt and decreased as salt decreased. For the red lentil, the Young’s modulus equation included the linear effects of flour (positive) and salt (negative), the quadratic effect of salt (positive), and the effect of the oil and flour interaction (positive). Young’s modulus values increased with flour and this effect was slightly enhanced by the oil content. The values decreased as the salt increased to a point of 0.9% addition, at which it started to increase slightly. Young’s modulus of chickpea gels depended on the flour content but also on salt and lemon, which indicated the negative interaction effect. As shown in Supplementary Figure S3, the values were high and stable in the range of salt addition studied (from 0% to 1.4%), when salt was used without lemon. The same happened with lemon (from 0% to 2.8%), when it was used without salt, but when they were used together at high levels, the values of the Young’s modulus decreased drastically. The penetration area of lentil and chickpea was positively related to flour and negatively to salt.
For red lentil, the effect of flour content varied with the salt and oil contents, as showed by the significant interaction effects. The increase in the penetration area with flour content was lower when the levels of salt were high. However, the effect of flour was higher at high levels of oil. The cutting force increased as the flour content increased for all pulses. For lentil, it was also negatively affected by the interaction of salt and flour, because the increase in cutting force with the flour content was lower at higher levels of salt. For the red lentil, the cutting force was also negatively related to salt and positively related to oil. It decreased as the salt increased from a limit to 0.9% in which it started to increase slightly. It increased with oil, and this increase was greater at high levels of salt. In chickpea gels, the cutting force was also negatively affected by the salt and oil interaction, because when they were used together at high levels, the cutting force decreased substantially. The mechanical properties of all pulse gels, regardless of the type of pulse, were affected by the flour and salt content. Hardness, gumminess, Young’s modulus, and resistance to penetration and cut decreased with salt within the studied range (0% to 1.4%) and increased with flour (15% to 17.5%).
Figure 14. Mechanical parameters of pulse gels made from flours of lentil (▲), red lentil (●), and chickpea (◼) obtained from the 17 formulations as shown in Table 12.
### Table 14. Regression models of the mechanical parameters of pulse gels as a function of the composition according to equation in Section 2.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flour Type</th>
<th>R²</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>Lentil</td>
<td>0.864</td>
<td>$-0.711 - 0.503\text{Salt} + 0.0087\text{Flour}^2$</td>
</tr>
<tr>
<td></td>
<td>Red lentil</td>
<td>0.939</td>
<td>$-0.85 + 0.419\text{Salt}^2 - 0.095\text{Oil}^2 + 0.010\text{Flour}^2 - 0.0649\text{Salt} \times \text{Flour} + 0.0271\text{Oil} \times \text{Flour}$</td>
</tr>
<tr>
<td></td>
<td>Chickpea</td>
<td>0.929</td>
<td>$-0.465 - 0.017\text{Lemon}^2 + 0.006\text{Flour}^2 - 0.015\text{Salt} \times \text{Flour}$</td>
</tr>
<tr>
<td>Gumminess</td>
<td>Lentil</td>
<td>0.857</td>
<td>$-0.690 - 0.473\text{Salt} + 0.00816\text{Flour}^2$</td>
</tr>
<tr>
<td></td>
<td>Red lentil</td>
<td>0.927</td>
<td>$-3.331 + 0.424\text{Salt}^2 - 0.096\text{Oil}^2 + 0.315\text{Flour} - 0.0631\text{Salt} \times \text{Flour} + 0.0272\text{Oil} \times \text{Flour}$</td>
</tr>
<tr>
<td></td>
<td>Chickpea</td>
<td>0.918</td>
<td>$-0.469 - 0.018\text{Lemon}^2 + 0.006\text{Flour}^2 - 0.014\text{Salt} \times \text{Flour}$</td>
</tr>
<tr>
<td>Young modulus</td>
<td>Lentil</td>
<td>0.673</td>
<td>$-0.00737 - 0.0036\text{Salt}^2 + 0.00015\text{Flour}^2$</td>
</tr>
<tr>
<td></td>
<td>Red lentil</td>
<td>0.765</td>
<td>$-0.0148 - 0.019\text{Salt} + 0.0037\text{Flour} + 0.0105\text{Salt}^2 + 0.0002\text{Oil} \times \text{Flour}$</td>
</tr>
<tr>
<td></td>
<td>Chickpea</td>
<td>0.885</td>
<td>$-0.010 + 0.000178\text{Flour}^2 - 0.0017\text{Salt} \times \text{Lemon}$</td>
</tr>
<tr>
<td>Penetration area</td>
<td>Lentil</td>
<td>0.934</td>
<td>$-4.939 - 2.552\text{Salt} + 0.059\text{Flour}^2$</td>
</tr>
<tr>
<td></td>
<td>Red lentil</td>
<td>0.759</td>
<td>$-16.77 + 1.175\text{Flour} - 0.1130\text{Salt} \times \text{Flour} + 0.0522\text{Oil} \times \text{Flour}$</td>
</tr>
<tr>
<td></td>
<td>Chickpea</td>
<td>0.735</td>
<td>$-5.572 - 0.769\text{Salt}^2 + 0.049\text{Flour}^2$</td>
</tr>
<tr>
<td>Cutting force</td>
<td>Lentil</td>
<td>0.946</td>
<td>$-0.258 + 0.0054\text{Flour}^2 - 0.015\text{Salt} \times \text{Flour}$</td>
</tr>
<tr>
<td></td>
<td>Red lentil</td>
<td>0.827</td>
<td>$-0.562 - 0.606\text{Salt} + 0.106\text{Flour} + 0.238\text{Salt}^2 + 0.0791\text{Salt} \times \text{Oil}$</td>
</tr>
<tr>
<td></td>
<td>Chickpea</td>
<td>0.872</td>
<td>$-0.339 + 0.005\text{Flour}^2 - 0.052\text{Salt} \times \text{Oil}$</td>
</tr>
</tbody>
</table>

**Note:** In the model equations, the superscript “2” indicates the quadratic effect of the factor and the “x” indicates the interaction between the two factors.
The effect of ingredients on the mechanical parameters of pulse gels may be explained by the interaction among ingredients and flour components that leads to changes in the conformed structure of the product (Patrascu et al., 2017). In this case, starches and proteins are the main components that contribute to the structure. Kaur and Singh (2005) reported that the gelation of pulse flours involves the formation of a polysaccharide–protein matrix. Starch granules swell during heating and after cooling to become more ordered and form a network (Pang et al., 2020). However, proteins can also form a network due to their aggregation resulting from denaturation during heating (Bresciani et al., 2022). Johansson et al. (2022) stated that proteins were the main contributors in the structure of gel formed by a mixture of starch, proteins, and fibers. According to Sharma et al. (2023), heating proteins promote hydrophobic interactions and disulfide bonds, therefore molecular unfolding and network conformation. For all the three pulses, flour content highly affected mechanical properties of gels. The increase in hardness, stiffness, and resistance of gels with flour content can be attributed to the greater amount of starch and proteins that leads to strengthening the structure of the formed network due to the presence of more solutes retaining water (Huang et al., 2019; Portman et al., 2019). Furthermore, a higher concentration of proteins and starch enhances the binding interactions among components, thus further strengthening the network.

The salt content also had a significant effect on the mechanical properties of all pulses. Increasing the salt content resulted in gels with lower hardness, gumminess, stiffness, and resistance to cutting and penetration. This effect could be attributed to the effect of salt on starches and protein solubility. According to Torres et al. (2014), considering that the presence of salts lowers water activity, it could result in delaying and limiting starch gelatinization, thus decreasing the strength of the protein–starch network. However, Langton et al. (2020) reported that protein solubility depends on the presence of salt and its amount. A higher amount of salt increases protein solubility, thus limiting their aggregation and precipitation, hence decreasing the strength of the gel network (Falkeisen et al., 2022; Renkema et al., 2002; Wang et al., 2023). Langton et al. (2020) and Johansson et al. (2023) studied the effect of different concentrations of NaCl on the gelation of different pulse proteins. The authors reported that the great repulsion between proteins results in higher solubility and thus in a more fine-stranded gel network.
The oil content affected the mechanical properties of the gels only in the case of red lentil. Increasing the oil content increased the hardness, gumminess, stiffness, and resistance of the red lentil gels. According to this, fat globules reinforce the structure of the starch–protein network. This effect could be explained by the higher emulsion capacity of red lentil flour compared to lentil and chickpea (Moussaoui et al., 2023). The emulsion particles aggregate due to protein denaturation after heating and lead to a stiffer gel (Sharma et al., 2023). The lemon juice content affected the mechanical properties of chickpea. Increasing the lemon content slightly reduced the hardness, gumminess, stiffness, and resistance of chickpea gels. These changes with lemon juice can be attributed to the effect of pH on starch and protein. Starch molecules can be hydrolyzed by the effect of acids, resulting in shorter amylose and amylopectin chains and decreasing the strength of gels (Hirashima et al., 2012; Jiménez et al., 2016). On the other side, the pH affects protein solubility depending on their isoelectric point (Ladjal-Ettoumi et al., 2016; Y. Wang et al., 2023). At pH far from the isoelectric point, protein solubility decreases, and results in an increase in their aggregation and a harder texture. The isoelectric point of chickpea proteins is stated to be ranging between 4 and 5 (Díaz et al., 2019). In this study, chickpea gels with a higher content of lemon juice had values of pH (5.2 to 5.3) closer to isoelectric point than those without lemon (6.3 to 6.4). Thus, the lowest rigidity of chickpea gels could be explained by the hydrolysis of starch molecules due to the acidity and the greater solubility of proteins since the pH of the formulation was slightly close from their isoelectric point, resulting in more fine-stranded gels. Lemon juice content also decreased the pH of lentil (5.5) and red lentil gels (5.5), but it did not significantly affect their mechanical properties. This indicated that not only the pH but also the type of proteins and starch of the pulse are relevant.

Red lentil flour forms gels that are harder, gummier, stiffer, and more resistant to cutting than lentil and chickpea gels. Chickpea gels form soft and less gummy gels that are less resistant to cutting but are stiffer than lentil gels. These differences seem to be attributed to different compositions of flours determined in a previous paper (Badia-Olmos et al., 2023). Lentil and red lentil gels with high protein content (25.9% and 24.0%, respectively) were harder, gummier, and more resistant than chickpea gels (16.9% protein). The higher fiber content for lentil flour (16.4%) appeared to help make the gels less rigid than chickpea (14.0% fiber) and were less rigid than for red lentil (9.8% fiber).
3.2 Sensory Properties of Pulse Gels

To describe the differences among pulse gels, participants generated between 12 and 23 attributes (16 on average). A total of 114 different terms were collected (46 for appearance, 35 for texture, and 33 for flavor). Appearance terms included those related to color (dark/light, yellow, white, and gray), brightness (bright), and homogeneity (uniform, smooth, and heterogeneous). To describe the texture of gels, participants used mainly terms related to mechanical properties (hard/soft, compact, melting in mouth, pasty, and gummy) but also related to surface properties (sandy, smooth, fibrous, rugous, and lumpy) and some others related to composition (wet and dry). Flavor attributes included those related to pulse flavor (pulse, lentil, and chickpea flavor), other ingredients (lemon flavor), basic tastes (sour, salty, and bitter), terms indicating flavor intensity (bland, mild, and intense flavor), and strange flavor.

Figure 15 shows the first two-dimensional plot resulting from the GPA of the sensory evaluation of lentil flour gels. In this plot, the attributes correlated with each factor (correlation > 0.6) are summarized in the box located at the corresponding extreme of the factor. The first factor (39.9% of total variability) differentiated lentil gels according to the flour content, but also the oil. The lentil gel with a low amount of flour (LF−Low) is separated on the left side of the plot, as it was perceived to have a lighter color and a fine, light texture that melts in the mouth. On the other extreme (right side), the two gels with a high amount of flour and oil (LF−High + O and LF−High + O + L) were perceived to have a harder, more compact and sandy texture and a more intense flavor. According to the position of the samples along the first factor, both the increase of the amount of flour and the addition of oil increased the hardness, compactness, sandiness, and flavor intensity of the lentil gels. The second factor (28.1% of variability) separates the samples according to the presence of lemon. Lentil gels with lemon (LF−Low + O + L and LF−High + O + L) are differentiated (on the bottom) with higher sourness, saltiness, and lemon flavor than the rest of the gels (on the top) that were perceived as having a darker color and with more lentil, pulse, and chickpea flavor, especially for those that have a high amount of flour (LF−High and LF−High-O). The differences in lentil gels depended on flour concentration and lemon and were perceived as having harder texture and intense and acid flavor at high amount of flour and presence of lemon.
Figure 15. Sensory map (first two dimensions of the GPA) representing the differences in lentil gels when varying the amount of flour (low and high) and adding sunflower oil (O) and lemon juice (L). The complete formulation of the products is shown in Table 13. In the box are included the attributes correlated with each dimension (r > 0.6), and in brackets the number of times each one is correlated is indicated.

Figure 16 shows the two-factor GPA plot for the red lentil flour gels. The first factor (47.0% of total variability) differentiated red lentil gels according to the presence of oil and lemon. On the left side, the red lentil gels prepared without oil and lemon (RF-low and RF-high) were perceived to have a lighter texture that melts in the mouth and a darker color. On the right, gels prepared with oil (RF-low + O and RF-high + O) and gels prepared with oil and lemon (RF-low + O + L and RF-high + O + L) were perceived as having a hard, compact, and sandy texture with a sour and intense flavor. According to the position of the samples along the first factor, the addition of oil and lemon increased the hardness, compactness, and intensity of the sour flavor of red lentil gels. The second factor (25.8% of variability) separates the samples according to the amount of flour. On the bottom, the red lentil gels appeared with a high amount of flour (RF-high, RF-high + O, and RF-high + O + L) and were perceived as having darker and intense pink color. At the top of the plot appeared red lentil gels with low amount of flour (RF-low, RF-low + O, and RF-low + O + L) with more intense pulse flavor and with particles.
Figure 16. Sensory map (first two dimensions of the GPA) representing the differences in red lentil gels when varying flour amount (low and high) and adding sunflower oil (O) and lemon juice (L). The complete formulation of the products is shown in Table 13. In the box are included the attributes correlated with each dimension ($r > 0.6$), and in brackets the number of times each one is correlated is indicated.

Figure 17 shows the two-factor GPA plot for chickpea flour gels. The first factor (43.8% of total variability) differentiated chickpea gels according to the amount of flour. On the left side, the three chickpea gels with low amounts of flour (CF−Low, CF−Low + O, and CF−Low + O + L) were perceived to have an intense chickpea and pulse flavor with a light texture that melts in the mouth. On the other extreme (right side), the gels with high amounts of flour (CF−High, CF−High + O, and CF−High + O + L) were perceived as having a harder and more compact texture. Therefore, increasing the amount of flour increases the hardness and compactness and reduces the taste of chickpea and the pulse of chickpea gels.

The second factor (29.3% of variability) separates the samples according to the presence of lemon. Lentil gels without lemon (LF−Low, LF−Low + O, LF−High, and LF−High + O) are differentiated (on the bottom) for having more pulse, chickpea, and lentil flavor. Gels with lemon (CF−low + O + L and CF−High + O + L) were perceived as sour, with an intense lemon flavor.
According to the position of the samples along this factor, the presence of lemon reduces the flavor of the pulse and chickpea and enhances the sour taste and the flavor of the lemon.

**Figure 17.** Sensory map (first two dimensions of the GPA) representing the differences in chickpea gels when varying the amount of flour (low and high) and adding sunflower oil (O) and lemon juice (L). The complete formulation of the products is shown in Table 13. In the box are included the attributes correlated with each dimension ($r > 0.6$), and in brackets the number of times each one is correlated is indicated.

The flour content affected mainly texture and flavor attributes in lentil and chickpea gels, whereas it affected mainly the appearance in red lentil gels. The lentil and chickpea gels were harder, firmer, and more compact when increasing the flour content. However, the sandiness sensation increased with the flour content of the lentil and decreased for the chickpea. Likewise, the intensity of the pulse (and lentil) flavor in lentil gels increased with flour content, whereas in chickpea gels pulse (and chickpea) flavor decreased with flour content. For all three pulses, including oil and lemon, the flavor of gels was affected with a reduction in the intensity of pulse, chickpea, or lentil flavors and an increase in sour taste and lemon flavor.
For the comparison of sensory differences among the different pulse types, a sensory evaluation of the three pulse gels used in this study was assessed. The two first factors plot resulting from the GPA of sensory evaluation are represented in Figure 18. For each factor, attributes showing a positive correlation (>0.6) or a negative correlation (<0.6) are listed at the corresponding extreme of the factor. The first factor (53.2% of total variability) separated chickpea and red lentil gels from lentil gels. On the right side, lentil gels were perceived as having a darker color, particles, sandy texture, and a more intense lentil and pulse flavor. On the left side, the chickpea and red lentil gels were perceived as compact, homogeneous, and with more yellow color and chickpea flavor. The second factor (23.9% of variability) separates red lentil from the chickpea gels. The red lentil gels were characterized by a pink color, being homogeneous, and melting in the mouth. In the bottom, the chickpea gels were perceived to have a harder, compact, and sandy texture.

In summary, each of the three pulses provide gels with distinctive sensory characteristics, which can be applied in the development of different types of solid plant-based products. The red lentil produces pink products with a homogeneous, creamy, and compact texture that melt in the mouth, which make it appropriate for the development of hard and soft plant-based cheeses. Chickpea also produces compact products that are harder and have more chickpea flavor, which make it appropriate for the development of sliceable or cold cuts such as products. Lentil gels have a sandy texture and are more intense in pulse and lentil flavor, making them suitable for the elaboration of spreadable products such as pate.

Furthermore, the sensory properties of the pulse products can be modulated by varying the flour, oil, and lemon juice concentrations, which can be used to optimize products according to the acceptability of consumers.
Figure 18. Sensory map (first two dimensions of the GPA) representing differences in products made with different pulse types (LF: Lentil flour, RF: Red lentil flour, CF: Chickpea flour) for formulations with high amounts of flour (high) and when including sunflower oil and lemon juice (O + L). In the box are included the attributes correlated with each dimension ($r > 0.6$), and in brackets the number of times each one is correlated is indicated.

4. CONCLUSIONS

Solid products (self-standing gels) can be obtained from heated dispersions of pulse flour (lentil, red lentil, and chickpea) at 15% to 17.5% inclusion, whose mechanical properties varied mainly depending on the type and content of the pulse flour. Red lentils provide harder, gummier, stiffer, and more resistant gels compared to chickpea and lentil gels. Chickpea gels form soft and less gummy gels that are less resistant to cutting but are stiffer than lentil gels. For the three pulses, the hardness, stiffness, and resistance of the gels increased with the flour content but decreased with the salt content. The different pulse gels displayed distinctive sensory properties, making them suitable for developing different types of solid plant-based products. Red lentil can be the base of soft or hard cheese-like products. Chickpea gels are more suitable for developing solid products that can be sliceable such as cold-cut products. Lentil gels are suitable for the elaboration of spreadable products such as pate. Therefore, the results of this research give insight into the suitability of these gels for the food industry, thus enhancing the variability and availability of...
plant-based food for attracting consumers that are seeking less processed, healthier, and sustainable food. However, more studies are required for the optimization of these products and that consider consumer opinions and preferences to direct the design of products with sensory properties that maximize consumer acceptance. Moreover, further studies considering the sustainability of the process, regarding the efficiency, waste, and the nutritional impact ratio of the product would be interesting for future investigations.

Supplementary Materials: The following supporting information can be found on Annex I or downloaded at: https://www.mdpi.com/article/10.3390/su15129407/s1, Figure S1: Response surface plots showing functional relationship between hardness of red lentil gels as a function of flour, salt, and oil concentrations. Model equation is shown in Table 14. The plot on the left side was generated considering a fixed concentration of oil at 1.4%. The plot on the right side was generated considering a fixed concentration of salt at 0.7%; Figure S2: Response surface plots showing functional relationship between hardness of chickpea gels as a function of flour, salt, and lemon concentrations. Model equation is shown in Table 14. The plot on the left side was generated considering a fixed concentration of salt at 0.7%. The plot on the right side was generated considering a fixed concentration of lemon at 1.4%; Figure S3: Response surface plots showing functional relationship between Young’s modulus of chickpea gels as a function of flour, lemon, and oil concentrations. Model equation is shown in Table 14. In this case, the plot was generated considering a fixed concentration of flour at 16.25%.

5. ACKNOWLEDGEMENTS

The authors of this article thank the Molendum Ingredientes (Zamora, Spain) for supplying the flours used in this study. Authors thank MCIN/AEI/10.13039/501100011033 for their financial support to the project PID2019 107723RB-C21.

The authors also acknowledge the Algerian government for the Pre-Doctoral scholarship offered to Djemaa Moussaoui giving an opportunity to carry out this study. To Spanish government MCIN/AEI for the Center of Excellence Accreditation Severo Ochoa (CEX2021-001189-S/MCIN/AEI/10.13039/501100011033).
3.3. STUDY 3

Evaluation of consumers’ response to plant-based burgers according to their attitude towards meat reduction

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Food quality and preference 2023; 110

DOI: 10.1016/j.foodqual.2023.104955
Evaluation of consumers’ response to plant-based burgers according to their attitude towards meat reduction

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KEYWORDS

Expected liking, Emotions, Healthy, Processed, Sustainable, Meat analogues.
ABSTRACT

This study aimed to measure the impact of the information about the type of plant-protein and consumers’ attitude towards meat reduction on consumers’ response to different plant-based burgers. 368 consumers assessed online the same image of a plant-based burger along with the information about the type of plant-protein (soy, pea or wheat (seitan)). Consumers’ attitude towards meat reduction was evaluated using a questionnaire related to meat consumption reduction. Expected liking, emotional response, healthy, processed and sustainable perception evoked by the samples were also evaluated. The information about the source of plant-protein had no effect on consumers’ response; however, a significant and strong effect of attitude towards meat reduction was found. Five groups of consumers were identified according to their attitude towards meat reduction. Supporters of meat reduction showed a high acceptance of plant-based burgers. Moreover, they perceived them as healthier, less processed and more sustainable. The opposite behaviour was observed for rejecters of meat reduction. Plant-based burgers evoked positive emotions on supporters, such as happy, secure and satisfied while negative emotions were evoked on rejecters (disgusted, adventurous and bored). These findings demonstrate the usefulness of the attitude towards meat reduction when segmenting consumers. Taking into account which aspects are the most important to consumers can be highly beneficial to the industry and food policy makers in the development of new products to replace animal protein-based options by healthier and more sustainable ones.
1. INTRODUCTION

In recent years, the growing health and environmental concerns of population have led to an interest in decreasing their use and consumption of animal-based products (Seo et al., 2023). Verain et al. (2017) indicated that the change towards less animal-based diets promote environmental benefits in addition to positive impacts on public health. Gebhardt (2020) stated that one among five consumers in Europe tend to decrease animal-based products consumption and this number is increasing exponentially. Meanwhile, the involvement of consumers in the shift towards healthy and sustainable diets requires more variety and availability of alternatives to meat-based products (Verain et al., 2017). It has been reported that the market of plant-based products is growing rapidly (Nolden & Forde, 2023). Plant-based sources of proteins know an increase in order to provide alternatives to meat proteins. Currently, soy and wheat are the leading plant-based proteins alternatives to meat proteins, but more recently pea protein has also gained a high relevance (Grasso et al., 2021). One of the keys to introduce or increase the consumption of new products for the food industry is to know reasons and drivers of consumers’ choices, preferences and opinions. Therefore, there is a keen interest among food industry to understand consumer response to plant-based meat analogues. Some authors have found that attitude towards meat reduction is relevant in consumers’ response towards several categories of plant and meat-based products (Tarrega et al., 2020; Weinrich & Elshiewy, 2019). Even though, less focus has been paid to understanding the factors that promote consumers’ preferences and attitudes to plant-based meat alternatives (Malek & Umberger, 2021).

It has been shown that other factors apart from liking are relevant for consumers to discriminate among products, such as the degree of healthiness, naturalness and sustainability of products (Hwang et al., 2020). Emotional response has been proved to provide also additional information that is helpful in the discrimination of consumers’ perception of meat alternatives (Orr et al., 2023; Schouteten et al., 2016). In this context, knowing consumers’ preferences and opinions about this kind of products can offer valuable insights to the food industry and food policy makers. This study aimed to measure the impact of the information about the source of plant-protein and the attitude towards meat consumption reduction on consumers’ response to plant-based burgers.
2. MATERIALS AND METHODS

2.1. Samples

The same image of a commercial plant-based burger with the information of its main source of plant-protein was used in this study (Figure 19). Soy, pea or wheat (seitan) were used as the plant-protein of each plant-based burger. Samples were identified with 3-digit random codes and presented at a randomized order to participants.

![Image of plant-based burgers with the source of plant-proteins used in the study.](image)

**Figure 19.** Image of plant-based burgers with the source of plant-proteins used in the study.

2.2. Participants

368 consumers (men = 150) aged between 18 and 65 years old (29.4 ± 11.3) participated in this study. No special criteria were used for choosing the participants. The volunteers were invited to participate by means of advertisements at the universities (Universidad Politécnica de Madrid and Universitat de Vic) and emails sent to consumers’ panel (SENS-UPM).

2.3. Procedure

The Ethics committee of Universitat Oberta de Catalunya (Reference CE23-TF03) approved the procedure. Participants gave their informed consent before participating in the study. They were also advised to use a tablet or computer (instead of a mobile phone) for better visibility of the questionnaire.

2.4. Questionnaire

The questionnaire was elaborated using Compusense Cloud Software (Compusense, Inc 2023, Guelph, Ontario, Canada). Participants received a link to the questionnaire by email.
2.4.1 Questions related to samples (expected liking, emotional response, and healthy, processed and sustainable perception)

Participants were asked to observe each sample before replying to different questions. First, participants were asked to rate their expected liking on a 9-point hedonic scale labelled from “dislike extremely” to “like extremely” at the left and right anchors of the scale, respectively. Then, for self-reported emotions, the Spanish version of the EsSense 25 lexicon was used (Dorado et al., 2016). Using a CATA ballot with the introductory statement “I think if I ate this product it would make me feel...”, participants were asked to choose all the emotional terms that applied to the displayed burgers. Emotion terms were randomized to avoid bias. After that, consumers’ perception of healthy, processed and sustainable were rated by line scales of 10 cm length. The scales were anchored on the extremes with labels from “not healthy” to “very healthy”, from “not processed” to “very processed” and from “not sustainable” to “very sustainable”, respectively.

2.4.2 Questions related to consumers

The last part of the questionnaire included questions about consumers’ attitude towards meat reduction, based on a previous study with slight modifications (Tarrega et al., 2020). Items evaluated were related to diet, habits, ethics, hedonism, health and environment using a 7-point Likert scale (from “strongly disagree” to “strongly agree”). Participants were asked to indicate their degree of agreement with the 32 statements, 13 of them reversed, related to meat consumption as shown in Table 15. Reversed items scores were duly processed before data analysis. Items of the questionnaire were randomized in order to avoid bias.

2.5. Data Analysis

Firstly, consumers’ attitude towards meat reduction was analysed by Exploratory Factor Analysis (EFA) with Varimax rotation. This analysis allowed grouping the items in new dimensions, according to their most relevant factors. Cronbach’s alpha was computed to determine the internal consistency of the items of the complete questionnaire and of each dimension.

Once the items were grouped into the new dimensions, the mean scores per dimension were calculated for each consumer and a cluster analysis was carried out by applying Euclidean distance and Ward’s method, with non-standardized data. Consumers’ classes were obtained and characterized by their mean values on the different dimensions. 1-way ANOVA was performed for each dimension to find out if there were significant differences between
consumer classes by dimension. 2-way ANOVAs were performed for expected liking, healthy, processed and sustainable perception in function of the source of plant-protein and consumers’ classes with double interaction. Tukey tests were used for ANOVA significant factors, in order to test significant differences between means.

Cochran test was applied to the CATA data on emotions to analyse the effect of the different sources of plant-protein on emotional response.

Chi-square tests were applied for each of the emotion terms in function of consumers’ classes. After filtering the significant emotions according to Chi-square tests, a Correspondence Analysis was applied to emotions data containing the consumers’ classes in rows and the significant emotions in columns. Each emotion term was decoupled in two variables in order to characterize the presence and absence of the emotion (suffix 1 and 0, respectively).

When appropriate, a significance level of 0.05 was used. XLSTAT (Addinsoft, 2023, New York, United States) and Statgraphics Centurion XIX (Statgraphics Technologies, Inc 2022, Virginia, United States) were used as statistical software.
Table 15. Items used for measuring attitude towards meat reduction.

<table>
<thead>
<tr>
<th>(+) Notation</th>
<th>Item</th>
<th>Reversed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diet 1</td>
<td>I need to eat meat to have enough energy</td>
<td>Yes</td>
</tr>
<tr>
<td>Diet 2</td>
<td>All things considered. meat is necessary in the human diet</td>
<td>Yes</td>
</tr>
<tr>
<td>Diet 3</td>
<td>If I couldn’t eat meat I would feel weak</td>
<td>Yes</td>
</tr>
<tr>
<td>Diet 4</td>
<td>Eating meat is important for a complete diet</td>
<td>Yes</td>
</tr>
<tr>
<td>Diet 5</td>
<td>Eating meat is part of a balanced lifestyle</td>
<td>No</td>
</tr>
<tr>
<td>Diet 6</td>
<td>It is possible to have an adequate diet without eating meat</td>
<td>No</td>
</tr>
<tr>
<td>Diet 7</td>
<td>Meat is irreplaceable in my diet</td>
<td>Yes</td>
</tr>
<tr>
<td>Environment 1</td>
<td>Eating meat has a negative impact on the environment</td>
<td>No</td>
</tr>
<tr>
<td>Environment 2</td>
<td>By eating meat I support an industry which is responsible for environmental damage</td>
<td>No</td>
</tr>
<tr>
<td>Environment 3</td>
<td>By eating meat. I'm also responsible for the problems associated with its production</td>
<td>No</td>
</tr>
<tr>
<td>Environment 4</td>
<td>To eat meat is disrespectful towards life and the environment</td>
<td>No</td>
</tr>
<tr>
<td>Ethic 1</td>
<td>It would be difficult for me to watch an animal being killed for food purposes</td>
<td>No</td>
</tr>
<tr>
<td>Ethic 2</td>
<td>If I had to kill the animals myself. I would probably stop eating meat</td>
<td>No</td>
</tr>
<tr>
<td>Ethic 3</td>
<td>If I saw an animal being killed. I would have no problems eating it</td>
<td>Yes</td>
</tr>
<tr>
<td>Ethic 4</td>
<td>I feel bad when I think about eating meat because of the animal suffering</td>
<td>No</td>
</tr>
<tr>
<td>Ethic 5</td>
<td>Eating meat reminds me of the death and suffering of the animals</td>
<td>No</td>
</tr>
<tr>
<td>Ethic 6</td>
<td>When I think about eating meat I feel guilty</td>
<td>No</td>
</tr>
<tr>
<td>Habit 1</td>
<td>I don't picture myself without eating meat regularly</td>
<td>Yes</td>
</tr>
<tr>
<td>Habit 2</td>
<td>I would feel fine with a meatless diet</td>
<td>No</td>
</tr>
<tr>
<td>Habit 3</td>
<td>It is easy to have a meat-free diet</td>
<td>No</td>
</tr>
<tr>
<td>Health 1</td>
<td>Eating meat frequently is not bad for your health</td>
<td>Yes</td>
</tr>
<tr>
<td>Health 2</td>
<td>Eating meat in excess has a negative impact on health</td>
<td>No</td>
</tr>
<tr>
<td>Health 3</td>
<td>A diet with lots of meat can be harmful to health</td>
<td>No</td>
</tr>
<tr>
<td>Health 4</td>
<td>If I ate less meat. my health would improve</td>
<td>No</td>
</tr>
<tr>
<td>Health 5</td>
<td>Eating less meat is good for my health</td>
<td>No</td>
</tr>
<tr>
<td>Hedonism 1</td>
<td>I love eating meat very much</td>
<td>Yes</td>
</tr>
<tr>
<td>Hedonism 2</td>
<td>I love meals with meat</td>
<td>Yes</td>
</tr>
<tr>
<td>Hedonism 3</td>
<td>I am a big fan of meat</td>
<td>Yes</td>
</tr>
<tr>
<td>Hedonism 4</td>
<td>Eating meat is one of the good pleasures in life</td>
<td>Yes</td>
</tr>
<tr>
<td>Hedonism 5</td>
<td>Meat disgusts me</td>
<td>No</td>
</tr>
<tr>
<td>Hedonism 6</td>
<td>Nothing can compare with a good steak</td>
<td>Yes</td>
</tr>
<tr>
<td>Hedonism 7</td>
<td>I do not like the taste of meat</td>
<td>No</td>
</tr>
</tbody>
</table>

Source: Extracted from Tarrega et al., (2020) with slight modifications. (+) Notations of items reflects dimensions according to Tarrega et al., (2020).
3. RESULTS AND DISCUSSION

3.1. Consumers’ classification according to their attitude towards meat reduction

Consumers were segmented into classes according to their degree of agreement with the 32 statements of attitude towards reducing meat consumption. The items were classified into six new dimensions based on the correlation between items and new dimensions according to EFA results (Table 16). The questionnaire presented good consistency in global terms (Cronbach’s alpha = 0.965). The new dimensions were similar to those that were pre-established in the questionnaire proposed by Tarrega et al. (2020) with slight differences. The hedonic dimension and the environment dimension remained as they were pre-established, without any change. Diet dimension was composed by all the seven diet items and by three new habit items. It was observed that Cronbach’s alpha increased when both dimensions were joined. As a result of EFA, ethical dimension was separated into two new dimensions: animal sacrifice and animal suffering. It was observed that the values from ethic 1 to ethic 3 were directly correlated to D4 and presented great consistency between them. The same happened with animal suffering; in which the values from ethic 4 to ethic 6 were more closely related to D3 and the statements were directly associated to animal suffering. Finally, in the health dimension, it was decided to eliminate the item Health 1, since it did not show good correlation with any dimensions, leaving the health dimension with four questions. Cronbach’s alpha within each new dimension showed good internal consistency for all of them, ranging between 0.800 and 0.944 (Table 16).

The cluster analysis segmented consumers into five classes according to the mean scores given for each new dimension of the questionnaire. A distinction was made between “high supporters”, “medium supporters”, “low supporters”, “partial rejecters” and “rejecters”, with the supporters (high, medium, low) being the most in agreement with reducing meat consumption, and the rejecters (partial and rejecters) being the most in disagreement with such reduction (Table 17).
**Table 16.** Correlation coefficients between items and new dimensions issued from the Exploratory Factor Analysis.

<table>
<thead>
<tr>
<th>Notation (a)</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>D6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hedonic 1</td>
<td><strong>0.902</strong></td>
<td>0.305</td>
<td>0.190</td>
<td>0.194</td>
<td>0.130</td>
<td>0.020</td>
</tr>
<tr>
<td>Hedonic 2</td>
<td><strong>0.840</strong></td>
<td>0.375</td>
<td>0.143</td>
<td>0.116</td>
<td>0.054</td>
<td>0.124</td>
</tr>
<tr>
<td>Hedonic 3</td>
<td><strong>0.817</strong></td>
<td>0.42</td>
<td>0.158</td>
<td>0.196</td>
<td>0.061</td>
<td>0.167</td>
</tr>
<tr>
<td>Hedonic 4</td>
<td><strong>0.772</strong></td>
<td>0.416</td>
<td>0.129</td>
<td>0.248</td>
<td>0.100</td>
<td>0.079</td>
</tr>
<tr>
<td>Hedonic 5</td>
<td><strong>0.677</strong></td>
<td>0.142</td>
<td>0.613</td>
<td>0.137</td>
<td>0.187</td>
<td>0.087</td>
</tr>
<tr>
<td>Hedonic 6</td>
<td><strong>0.676</strong></td>
<td>0.441</td>
<td>0.092</td>
<td>0.306</td>
<td>0.156</td>
<td>0.158</td>
</tr>
<tr>
<td>Hedonic 7</td>
<td><strong>0.671</strong></td>
<td>0.071</td>
<td>0.419</td>
<td>0.142</td>
<td>0.162</td>
<td>0.104</td>
</tr>
<tr>
<td>Diet 1</td>
<td>0.354</td>
<td><strong>0.821</strong></td>
<td>0.022</td>
<td>0.147</td>
<td>0.040</td>
<td>0.167</td>
</tr>
<tr>
<td>Diet 2</td>
<td>0.373</td>
<td><strong>0.775</strong></td>
<td>0.177</td>
<td>0.158</td>
<td>0.328</td>
<td>0.072</td>
</tr>
<tr>
<td>Diet 3</td>
<td>0.482</td>
<td><strong>0.767</strong></td>
<td>0.190</td>
<td>0.156</td>
<td>0.240</td>
<td>0.057</td>
</tr>
<tr>
<td>Diet 4</td>
<td>0.365</td>
<td><strong>0.763</strong></td>
<td>0.017</td>
<td>0.141</td>
<td>0.022</td>
<td>0.176</td>
</tr>
<tr>
<td>Diet 5</td>
<td>0.423</td>
<td><strong>0.699</strong></td>
<td>0.243</td>
<td>0.193</td>
<td>0.243</td>
<td>0.101</td>
</tr>
<tr>
<td>Diet 6</td>
<td>0.144</td>
<td><strong>0.679</strong></td>
<td>0.287</td>
<td>0.237</td>
<td>0.239</td>
<td>0.328</td>
</tr>
<tr>
<td>Diet 7</td>
<td>0.562</td>
<td><strong>0.626</strong></td>
<td>0.122</td>
<td>0.215</td>
<td>0.195</td>
<td>0.175</td>
</tr>
<tr>
<td>Habit 2</td>
<td>0.420</td>
<td><strong>0.526</strong></td>
<td>0.445</td>
<td>0.255</td>
<td>0.271</td>
<td>0.263</td>
</tr>
<tr>
<td>Habit 3</td>
<td>0.296</td>
<td><strong>0.475</strong></td>
<td>0.327</td>
<td>0.127</td>
<td>0.026</td>
<td>0.201</td>
</tr>
<tr>
<td>Habit 1</td>
<td>0.588</td>
<td><strong>0.561</strong></td>
<td>0.205</td>
<td>0.205</td>
<td>0.065</td>
<td>0.135</td>
</tr>
<tr>
<td>Ethic 5</td>
<td>0.491</td>
<td>0.216</td>
<td><strong>0.699</strong></td>
<td>0.394</td>
<td>0.203</td>
<td>0.106</td>
</tr>
<tr>
<td>Ethic 4</td>
<td>0.421</td>
<td>0.228</td>
<td><strong>0.651</strong></td>
<td>0.513</td>
<td>0.192</td>
<td>0.121</td>
</tr>
<tr>
<td>Ethic 6</td>
<td>0.495</td>
<td>0.226</td>
<td><strong>0.617</strong></td>
<td>0.319</td>
<td>0.267</td>
<td>0.144</td>
</tr>
<tr>
<td>Ethic 1</td>
<td>0.233</td>
<td>0.165</td>
<td>0.252</td>
<td><strong>0.873</strong></td>
<td>0.193</td>
<td>0.123</td>
</tr>
<tr>
<td>Ethic 2</td>
<td>0.263</td>
<td>0.264</td>
<td>0.185</td>
<td><strong>0.768</strong></td>
<td>0.261</td>
<td>0.184</td>
</tr>
<tr>
<td>Ethic 3</td>
<td>0.397</td>
<td>0.228</td>
<td>0.070</td>
<td><strong>0.678</strong></td>
<td>0.107</td>
<td>0.111</td>
</tr>
<tr>
<td>Environment 1</td>
<td>0.186</td>
<td>0.352</td>
<td>0.168</td>
<td>0.333</td>
<td><strong>0.798</strong></td>
<td>0.368</td>
</tr>
<tr>
<td>Environment 2</td>
<td>0.104</td>
<td>0.204</td>
<td>0.295</td>
<td>0.289</td>
<td><strong>0.625</strong></td>
<td>0.198</td>
</tr>
<tr>
<td>Environment 3</td>
<td>0.177</td>
<td>0.192</td>
<td>0.232</td>
<td>0.285</td>
<td><strong>0.584</strong></td>
<td>0.315</td>
</tr>
<tr>
<td>Environment 4</td>
<td>0.250</td>
<td>0.407</td>
<td>0.392</td>
<td>0.450</td>
<td><strong>0.542</strong></td>
<td>0.229</td>
</tr>
<tr>
<td>Health 2</td>
<td>0.126</td>
<td>0.115</td>
<td>0.084</td>
<td>0.125</td>
<td>0.202</td>
<td><strong>0.895</strong></td>
</tr>
<tr>
<td>Health 3</td>
<td>0.066</td>
<td>0.185</td>
<td>0.048</td>
<td>0.132</td>
<td>0.111</td>
<td><strong>0.863</strong></td>
</tr>
<tr>
<td>Health 5</td>
<td>0.189</td>
<td>0.271</td>
<td>0.251</td>
<td>0.139</td>
<td>0.239</td>
<td><strong>0.556</strong></td>
</tr>
<tr>
<td>Health 4</td>
<td>0.242</td>
<td>0.278</td>
<td>0.376</td>
<td>0.070</td>
<td>0.315</td>
<td><strong>0.411</strong></td>
</tr>
</tbody>
</table>

**Cronbach’s Alpha**<sup>(b)</sup>  | **0.944** | **0.938** | **0.908** | **0.850** | **0.849** | **0.800** |

**Note:** (a) Items notation and meaning are presented in Table 15. (b) Cronbach’s alpha per dimension.
Table 17. Descriptive analysis of consumers’ classes related to the attitude towards meat reduction.

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Class</th>
<th>n</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rejecters</td>
<td>C1</td>
<td>81</td>
<td>2.48 (1.51)</td>
</tr>
<tr>
<td>Partial rejecters</td>
<td>C2</td>
<td>67</td>
<td>3.05 (1.33)</td>
</tr>
<tr>
<td>Low supporters</td>
<td>C3</td>
<td>128</td>
<td>4.05 (1.50)</td>
</tr>
<tr>
<td>Medium Supporters</td>
<td>C4</td>
<td>62</td>
<td>5.39 (1.22)</td>
</tr>
<tr>
<td>High Supporters</td>
<td>C5</td>
<td>30</td>
<td>6.56 (0.56)</td>
</tr>
<tr>
<td>Global</td>
<td></td>
<td>368</td>
<td>3.95 (1.85)</td>
</tr>
</tbody>
</table>

*Note: Measured by Likert scale from 1: strongly disagree to 7: strongly agree.*

**Figure 20** shows the characterization of each class together with the results of the Tukey tests per dimension. In general, high supporters (C5) gave significantly higher scores for all dimensions. Medium supporters (C4) showed a greater difference among dimensions’ mean scores, two points below high supporters (C5) in most dimensions. The low supporters (C3) had significantly lower scores than medium and high sup- porters (C4 and C5 respectively), giving moderate to high scores for the dimensions of diet, animal sacrifice, environment and health, and lower scores for hedonics and animal suffering. Partial rejecters (C2) gave more importance to the animal sacrifice and health as compared to other dimensions. Rejecters (C1) gave low scores to most dimensions, significantly lower to partial rejecters (C2), except for environment (not significantly different from C2) and health (significantly higher than C2).

Dagevos, (2021) reported that environmental sustainability and human health are the first drivers for reduction of meat consumption among consumers. Our study supports these findings, nevertheless, we found that the degree of motivation varies among consumers’ classes. Supporters believe that meat consumption promote negative health and environmental issues (Cliceri et al., 2018). Furthermore, Graça et al. (2015) reported that degree of attachment to meat eating could be a crucial reason for the acceptance or rejection of consumers towards meat reduction. This could explain the subdivision of the groups of supporters, wherein medium and low supporters, in fact tend to reduce meat consumption for health and environmental aspects; however, they were less concerned by animal suffering and hedonic aspects.

Our finding also support reports of previous studies (Lacroix & Gifford, 2020; Malek & Umberger, 2021). Authors identified some groups among consumers named as “meat eaters” or “lovers” that are less or not willing to decrease meat consumption nor to replace it, mainly for hedonic reasons and low concern about environment and animal welfare issues. Two
subgroups were identified in our study due to the difference in scores given to meat reduction dimensions among rejecters. This agrees with several previous studies that showed that even among meat eaters there are some groups that are not highly in favour with reducing meat consumption but are conscious of the environmental impact of meat consumption, even if this knowledge is still not decisive in their choices for meat reduction (De Boer et al., 2017; Graça et al., 2015).

![Profile plot]

**Figure 20.** Description of consumers’ classification by dimensions. Note: For each dimension, different letters indicate statistically significant differences between classes according to Tukey test ($p \leq 0.05$).

3.2 Effect of the source of plant-protein and consumers’ classes on consumers’ response to plant-based burgers

Results of ANOVA showed that there was no significant effect of the source of plant-protein (soy, pea or wheat) on the expected liking, perception of healthy, processed and sustainable (**Table 18**). Similarly, results of the Cochran test showed that there was no significant effect of the information about the source of plant-protein on emotional response (results not shown). In agreement, Tarrega et al. (2020) reported that there was no significant difference in the expected liking of soy and seitan burgers among the different groups of meat reduction attitude. Their research assessed consumers’ response to mixed meat and vegetable products by Spanish consumers. However, in another study where pea and soy were used as second ingredient in the
context of meat substitute based on micro-algae; authors found that pea was preferred to soy (Weinrich & Elshiewy, 2019). In the latter study, the results were based on an online survey with 940 participants from Germany, Netherlands and France (Weinrich & Elshiewy, 2019). It seems that the effect of the source of plant-protein on acceptance of plant-based products could depend on the product nature and/or on the cultural origin of consumers. Results of ANOVA showed that there was significant effect of consumers’ classes on the expected liking, healthy, processed and sustainable perception.

Table 18. p-Values of the 2-way ANOVAs on expected liking, healthy, processed and sustainable perception in function of plant-protein and consumer class.

<table>
<thead>
<tr>
<th></th>
<th>Plant-protein</th>
<th>Consumer class</th>
<th>Plant-protein * Consumer class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Liking</td>
<td>0.1965</td>
<td>&lt;0.0001</td>
<td>0.5389</td>
</tr>
<tr>
<td>Healthy</td>
<td>0.1965</td>
<td>&lt;0.0001</td>
<td>0.7400</td>
</tr>
<tr>
<td>Processed</td>
<td>0.9728</td>
<td>0.0351</td>
<td>0.9999</td>
</tr>
<tr>
<td>Sustainable</td>
<td>0.2602</td>
<td>&lt;0.0001</td>
<td>0.9982</td>
</tr>
</tbody>
</table>

**Note:** Values in bold are statistically significant ($p \leq 0.05$).

Mean value of expected liking was $5.95 \pm 1.06$ on a 9-point scale, indicating that plant-based burgers were globally slightly accepted. Mean values of the expected liking of plant-based burger according to consumers’ classes and results of Tukey tests are shown in Figure 21. Not surprisingly, C3, C4 and C5 that are low, medium and high supporters gave significantly higher scores on expected liking as compared to classes C1 and C2 that are rejecters of reduction of meat consumption. In the same line, Graça et al. (2015) stated that consumers’ preferences and acceptance of plant-based food depend on their attitude and attachment to meat consumption. Healthy, processed and sustainable perception of plant-based burgers according to consumers’ classes and results of Tukey test are shown in Figure 22.

Healthy perception was moderate ($6.45 \pm 0.53$) on a 10 cm line and it varied slightly according to consumers’ classes. The most relevant difference was observed between C2 and C3 that are partial rejecters and low supporters respectively. This finding is in accordance with the description of consumers’ classes by health dimension (Figure 20), since C3, even though the low to moderate scores they gave to some dimensions, they showed high intention to meat reduction for health concerns. Yet, C2 was characterised by the lowest scores given to the health dimension among all consumers’ classes reflecting the lowest interest in meat reduction for health concerns.
Figure 21. Effect of consumers’ classes on expected liking of plant-based burgers. Different letters indicate significant differences according to Tukey test (p ≤ 0.05). Note: C1: rejecters, C2: partial rejecters, C3: low supporters, C4: medium supporters, and C5: high supporters of reduction of meat consumption.

In general, consumers perceived all plant-based burgers as slightly processed (5.97 ± 0.28). Processed perception also varied slightly with consumers’ classes, nevertheless, the only significant difference was found between C1 and C4. Consumers of C1 (rejecters) perceived the plant-based burgers as significantly more processed than consumers of C4 (medium supporters). Sustainable perception of samples was moderate (6.42 ± 0.89).

Rating scores varied with consumers’ classes. C4 and C5 that are medium and high supporters of reducing meat consumption gave significantly higher scores on sustainable perception as compared to C1 and C2 that are rejecters of meat reduction. This finding supports the environment dimension differences observed between C4 and C5 (showing high intention in meat reduction for environmental concerns) as compared to C1 and C2 whose means on this dimension were around 3-points below C4 and C5 (Figure 20). Prior researches assessed on plant-based product found that consumers, in general, perceive these products as healthier and more sustainable as compared to meat-based products (Rondoni et al., 2021; Sucapane et al., 2021).

Our results are also in accordance with previous reports on consumers’ awareness about sustainability (Verain et al., 2017). The latter segmented consumers according to the importance they attach to sustainability, health, taste and price of food in several food categories. Authors
reported the distinction of a group of consumers that was called “sustainable conscious consumers” that showed higher intention to reduce meat consumption for environmental sustainability concerns as compared to the other groups.

Figure 22. Effect of consumers’ classes on healthy, processed and sustainable perception of plant-based burgers. Different letters within the same variable indicate significant differences between consumers’ classes according to Tukey test (p ≤ 0.05). Note: C1: rejecters, C2: partial rejecters, C3: low supporters, C4: medium supporters, and C5: high supporters of reduction of meat consumption.

Regarding emotional response, a significant effect of consumers’ classes on 20 out of 25 emotions was found. Frequency counts of significant emotions by consumers’ classes are displayed in Table 19. Some emotions that were significant but did not meet theoretical frequencies requirement of Chi-square test can be found in Table S1.

Concerning rejecters of meat reduction, interesting differences were found between both groups. As compared to the expected frequencies under the null hypothesis, C1 (rejecters) was characterized by higher frequencies of adventurous, bored and disgusted and lower frequencies of happy, joyful, pleasant, good, secure, mild and satisfied. C2 (partial rejecters) was characterized by higher frequencies of bored and tame and lower frequencies of happy, good-natured, joyful, good, satisfied and mild.

Looking at the differences between supporters C3, C4 and C5 (low, medium and high supporters, respectively), C3 was characterized by higher frequency of good-natured, joyful and mild and lower frequency of disgusted. Moreover, C4 and C5, were characterized by higher frequencies of happy, interested, good and secure. In the case of C4, higher frequencies of
pleasant, adventurous and satisfied and lower of bored and disgusted were also observed. For C5 higher frequencies of good-natured, free and joyful were found.

**Table 19.** Frequency counts of significant emotions by consumers’ classes.

<table>
<thead>
<tr>
<th>Emotion Terms</th>
<th>C1 (Rejecters)</th>
<th>C2 (Partial rejecters)</th>
<th>C3 (Low supporters)</th>
<th>C4 (Medium supporters)</th>
<th>C5 (High supporters)</th>
<th>Total citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Happy</td>
<td>15*&lt;</td>
<td>10*&lt;</td>
<td>42</td>
<td>39*&gt;</td>
<td>27*&gt;</td>
<td>133</td>
</tr>
<tr>
<td>Good-natured</td>
<td>13</td>
<td>4*&lt;</td>
<td>34*&gt;</td>
<td>10</td>
<td>12*&gt;</td>
<td>73</td>
</tr>
<tr>
<td>Free</td>
<td>22</td>
<td>20</td>
<td>27</td>
<td>16</td>
<td>16*&gt;</td>
<td>101</td>
</tr>
<tr>
<td>Joyful</td>
<td>18*&lt;</td>
<td>3*&lt;</td>
<td>55*&lt;</td>
<td>22</td>
<td>27*&gt;</td>
<td>125</td>
</tr>
<tr>
<td>Interested</td>
<td>49</td>
<td>38</td>
<td>86</td>
<td>26*&lt;</td>
<td>27*&gt;</td>
<td>226</td>
</tr>
<tr>
<td>Pleasant</td>
<td>24*&lt;</td>
<td>25</td>
<td>68</td>
<td>51*&gt;</td>
<td>20</td>
<td>188</td>
</tr>
<tr>
<td>Good</td>
<td>30*&lt;</td>
<td>21*&lt;</td>
<td>74</td>
<td>46*&gt;</td>
<td>30*&gt;</td>
<td>201</td>
</tr>
<tr>
<td>Adventurous</td>
<td>48*&gt;</td>
<td>22</td>
<td>60</td>
<td>11*&gt;</td>
<td>7</td>
<td>148</td>
</tr>
<tr>
<td>Secure</td>
<td>6*&lt;</td>
<td>15</td>
<td>44</td>
<td>30*&gt;</td>
<td>15*&gt;</td>
<td>110</td>
</tr>
<tr>
<td>Active</td>
<td>17</td>
<td>13</td>
<td>46</td>
<td>19</td>
<td>14</td>
<td>109</td>
</tr>
<tr>
<td>Satisfied</td>
<td>43*&lt;</td>
<td>47*&lt;</td>
<td>121</td>
<td>96*&gt;</td>
<td>56*&gt;</td>
<td>363</td>
</tr>
<tr>
<td>Tame</td>
<td>31</td>
<td>35*&gt;</td>
<td>37</td>
<td>17</td>
<td>2</td>
<td>122</td>
</tr>
<tr>
<td>Mild</td>
<td>9*&lt;</td>
<td>6*&lt;</td>
<td>47*&gt;</td>
<td>10</td>
<td>2</td>
<td>74</td>
</tr>
<tr>
<td>Bored</td>
<td>49*&gt;</td>
<td>32*&gt;</td>
<td>37</td>
<td>5*&lt;</td>
<td>5</td>
<td>128</td>
</tr>
<tr>
<td>Disgusted</td>
<td>62*&gt;</td>
<td>22</td>
<td>27*&lt;</td>
<td>5*&lt;</td>
<td>1&lt;</td>
<td>117</td>
</tr>
</tbody>
</table>

**Note:** Values displayed with asterisk are statistically significant. Symbols > and < means respectively that observed frequencies are significantly higher or lower than expected under the null hypothesis ($p \leq 0.05$).
To summarize the emotional response evoked by samples according to consumers’ classes, a Correspondence Analysis was applied on the discriminant emotions data (see Tables 19 and S1). Only emotions that showed a good quality of projection (sum of squared cosines > 0.5) were displayed on the plots (Figure 23).

Figure 23a shows the projection of the classes on the first two factors, which represent 89.44% of the total variance. As it can be observed, the first factor, which accounts for 79.09% of the variance, separated consumers’ classes according to their degree of agreement with meat reduction. On the left part, medium and high supporters are located and characterised by being satisfied, happy, good, secure, pleasant and not bored, nor disgusted (Figure 23b). This indicates that the agreement with reducing meat consumption can be explained, not only by the preferences of these consumers, but also by their perception of healthiness of this kind of products that evoked emotions such as secure. The opposite behaviour was observed for partial rejecters and rejecters, which appear associated, not only to disgusted and bored, but also to adventurous, wild and not secure.
Figure 23. Projection of consumers’ classes (a) and emotions (b) on the first two axes of the Correspondence Analysis. Note (a): C1: rejecters, C2: partial rejecters, C3: low supporters, C4: medium supporters, and C5: high supporters of reduction of meat consumption. Note (b): Displayed emotions are filtered according to the quality of projection in the plot (cos^2 > 0.5). For each emotion, suffix 0 means absence and suffix 1 means presence.
The second factor accounts for 10.38% of the total variance. This factor is mainly related to the level of activation of consumers towards reducing meat consumption. It separated the more radical groups C1 and C5 on the bottom of the plot, from the more moderate groups C2 and C4 that are on the top (Figure 23a). This separation is mainly attributed to the presence of emotions such as joyful, interested and good-natured on the one hand (positive valence) and adventurous and disgusted on the other hand (negative valence) (Figure 23b). It is to note that expected liking and sustainable perception showed a similar trend, being the more ‘activated’ groups (C5 and C1) the ones with the highest and lowest scores (respectively) on both variables. Moreover, C1 and C2 are separated by their projection on the second axis, probably due to the differences on the disgusted term (62 vs 22), on the one hand, and adventurous (48 vs 22), wild (17 vs 5) and secure (6 vs 15), on the other hand (Table 19). Although disgusted is an emotion related to hedonic dimension, the terms adventurous, wild and secure linked to C1 could be associated to health concerns. Even though C1 and C2 did not show significant differences on healthy perception of plant-based burgers (Figure 22), consumers of C2 were not concerned, in general, by health dimension as compared to C1 when considering the reduction of meat consumption (Figure 20).

C3, which are low supporters, is not well represented in this projection. It is located on the central part of the plot due to the emotions related to the third factor. Projection plots on the first and third axes are displayed in Figure 24. The third factor accounts for 7.43% of the total variance. It can be observed (Figure 24a) that the third axis separates C3 (on the top of the plot) from all the other groups (on the low part). This separation is mainly attributed to the emotion mild (Figure 24b). Frequency count of mild in C3 (47) is significantly higher than expected under the null hypothesis (Table 19). Furthermore, terms not having a good quality of projection on the first factorial plot appear well represented on the low part of the third axis, close to C1 and C2, such as guilty, wild and free. This helps in the understanding of the perception towards this kind of products by C1 and C2 that are rejecters of meat reduction.

According to De Boer et al. (2017) the most driver reasons of the less willingness of meat eaters to reduce meat consumption is that they are attached to meat eating and they believe that eating meat frequently is healthy. Attachment to meat eating is in accordance with our results that showed low willingness of rejecters to reduce meat consumption for hedonics reasons. Even though, according to our results, rejecters gave higher scores to reduction of meat consumption when it concerns their health. Rejecters’ behaviour may be due to a higher processed perception of plant-based burgers. This agrees with Hwang et al. (2020) and Varela
et al. 2022) which reported that unnaturalness perception was considered among the common negative factors affecting acceptance of plant-based meat alternatives.

**Figure 24.** Projection of consumers’ classes (a) and emotions (b) on the axes one and three of the Correspondence Analysis. **Note (a):** C1: rejecters, C2: partial rejecters, C3: low supporters, C4: medium supporters, and C5: high supporters of reduction of meat consumption. **Note (b):** Displayed emotions are filtered according to the quality of projection in the plot (cos2 > 0.5). For each emotion, suffix 0 means absence and suffix 1 means presence.
Cliceri et al. (2018) stated that the acceptance of plant-based products depends on taste and food properties besides of ethical and health aspects. This could reveal a relationship between the positive emotions that supporters of reduction of meat consumption gave; and the highest liking of plant-based burgers.

It is worthy to note that emotional response to plant-based burgers provides a better understanding of differences among consumers’ groups, beyond expected liking and perceptions. It is also important to note that emotions evoked by plant-based burgers are highly affected by consumers’ attitude towards meat reduction. This confirms that the higher liking observed by supporters is due to preferences of consumers to this kind of products in accordance with positive emotions of pleasure and security. On the other hand, unhealthy and processed perception could be attributed to the negative emotions that rejecters feel towards this kind of products. Reported feelings of adventurous and wild could reveal some fear from replacing or changing their usual products by new ones that are imitations. Orr et al. (2023) and Tarrega et al. (2020) mentioned uncertainty and unfamiliarity among the main barriers for consumers to explore meat alternatives.

4. CONCLUSION

The information about the source of plant-protein (soy, pea or seitan (wheat)) had no effect on consumers’ response, however, a significant and strong effect of attitude towards meat reduction was found. Five groups of consumers were identified according to their attitude towards meat reduction, considering six dimensions (hedonic, diet, environment, animal suffering, animal sacrifice and health). Results from this study have led to a deeper understanding on the impact of the attitude towards meat reduction on consumers’ response to plant-based products. It confirms that environmental sustainability, animal welfare and health concerns are the main drivers of meat reduction, while meat attachment and feelings of adventurous and wild evoked by the plant-based products are the main barriers to such reduction. The classification according to the attitude towards reducing meat consumption demonstrate its usefulness for segmenting consumers. Taking into account which aspects are most important to consumers in relation to their attitudes can be helpful to the industry in the development of new products to replace animal protein-based options by more sustainable ones. Hence, it provides useful information to policy makers for the development of food guidelines promoting animal-to-plant-protein transition. For this purpose, it would be
interesting and beneficial to have a shortened version of the questionnaire about consumers’ attitude towards meat reduction, easier to include in future studies. Deeper thinking on the consideration of natural/processed perception of this kind of products is advised in order to gain better understanding of meat lovers’ behavior. Moreover, further research including product tasting is needed to find out if the exposure to the sensory properties of the products contributes or modulate the expectations that are mainly driven by consumers’ attitude towards meat reduction.

5. ACKNOWLEDGEMENTS

Funding from Fundación Premio Arce (FPA190000PPECO1) and Government of Catalonia - Agency for Management of University and Research Grants (AGAUR) (2022/ DI / 00027) is acknowledged. Authors thank Ministerio de Ciencia e Innovacion (MCIN/AEI/10.13039/501100011033) for their financial support to the project PID2019 107723RB-C21. The authors also acknowledge the Algerian Government for the Pre-Doctoral scholarship offered to Djemaa Moussaoui.

6. SUPPLEMENTARY DATA

Supplementary data to this article can be found on Annex I, and online at https://doi.org/10.1016/j.foodqual.2023.104955 and on the appendix of this thesis.
4. Chapter 4. General Discussion
4.1. Main Findings

The objective of the present thesis was to explore the potential of plant-ingredients for the development of novel plant-based food and to achieve a better understanding of consumers’ response towards plant-based food products. Therefore, the thesis was designed in two research topics. The first research topic is presented in studies one and two. It deals with various physicochemical aspects of pulse flours as base ingredients for the development of novel plant-based food that offers a good nutritional value, particularly in terms of proteins. The second research topic is presented in studies 3 and four that deal with consumers’ response to plant-based food as an alternative source of protein to animal-based food, as well as investigating the factors that affect their response. The studies three and four contribute to the second research topic. Overall, both topics provide a deeper insight into crucial aspects of the entire process of the transition towards healthy and more sustainable food systems, including product development and consumer response.

4.1.1 Exploring the potential of pulse flours for the development of plant-based products.

As previously mentioned, our first purpose was to evaluate the potential of pulse flours for the development of novel plant-based products. Pulses were selected since they provide numerous advantages from health and environment perspectives. Pulses are eco-friendly crops that are rich in proteins offering a source of several essential amino acids besides of other nutrients such as carbohydrates and dietary fibres (Iriti & Varoni, 2017). From a technological point of view the use of pulse flours offers an ingredient that is affordable, cost-effective and less processed as compared to protein isolates or concentrates for the elaboration of plant-based products. Previous studies reported that the versatile composition of pulse flours as well as their high protein content provide a great choice for the elaboration of various kinds of products depending on the used process (Gupta et al., 2018; Kaur & Singh, 2005; Shevkani et al., 2021). Previous studies have been conducted to evaluate the effect of different treatments on the functional properties of pulses flours. For instance, Ferawati et al., (2019) evaluated changes in the effect of boiling, roasting and germination on the techno-funcional properties of pulse flours. Authors reported that the different treatments studied enhanced water absorption and gelation, while emulsion and foaming properties decreased. Nevertheless, no studies were conducted to evaluate the effect of acidic conditions or of the presence of calcium on the techno-functional properties of pulse flours.

In the first study of this thesis, the techno-functional properties of four pulse flours were investigated when ionic strength and pH were varied. The techno-functional properties of the
four pulse flours studied varied depending on the pulse type and the condition. At natural condition, white bean flour showed higher water holding capacity than the rest of pulses. Decreasing pH and adding calcium improved the water holding capacity of all pulse flours revealing an improvement in hydration ability, which should be considered for the elaboration of products that requires higher moisture retention. Aziah and Komathi, (2009) reported that higher water holding capacity improves the mouthfeel and decrease syneresis in food products. All the pulse flours showed higher emulsifying capacity at natural condition as compared to the other conditions studied. Lentil and red lentil flours produced more foam that was more stable over time than white bean and chickpea flours. The presence of calcium at more acidic conditions improved foaming properties. According to our findings, pulse flours provide better emulsion at natural condition, which make them good candidates for the formulation of soups, sauces, and doughs. Meanwhile, considering acidic condition and the presence of calcium helps in the formation of greater foam with higher stability, which could be intended in food preparations such as ice cream and milkshake as well as baking and confectionery where sponginess is required. Similar findings were reported in previous studies in terms of foaming and emulsifying properties of pulse flours under ambient conditions (Ettoumi & Chibane, 2015; Sreerama et al., 2012). Previous studies highlighted the significant role of the type and the amount of proteins in foaming and emulsifying properties, which explain the high foaming and emulsifying capacities of all the pulse flours studied when linked to their high protein content (Aluko et al., 2009; Shevkani et al., 2021). Furthermore, it was reported that foaming and emulsifying properties might be influenced not only by the amount of protein present, but also by its solubility, that depend on the pH (M. Jarpa-Parra et al., 2015; Shevkani et al., 2019). Accordingly, changes in foaming and emulsifying properties of pulse flours with studied condition can be explained by the increase or decrease of protein solubility. Other components such as polysaccharides were also reported to their ability to interact with proteins, thus influencing the emulsifying properties of flours (Osemwota et al., 2021).

Viscosity profile of pulse flours during thermomechanical treatment, showed that at natural condition, chickpea flour provided higher viscosity to the water dispersion than the rest of pulses. The effects of pH and calcium on the pasting temperature, maximum viscosity during heating, and final viscosity, were similar for all flours except for white bean. By lowering the pH to 5 and 3, the viscosity of pulse flour pastes was improved and the pasting temperature was decreased. For lentil, red lentil, and chickpea flours, the effect of decreasing pH to 5 or 3 was lower when calcium was added, but higher for white bean flours.
According to the literature, viscosity of flour dispersions during shearing and heating is mainly linked to starch gelatinisation phenomena (Li et al., 2014). Previous studies stated that other component such as proteins, fiber, and lipid also can affect viscosity properties (Adebowale & Adebowale, 2007; Lee et al., 2024). According to our results, changes in viscosity of pulse flours when decreasing pH and adding calcium along with the observed differences among pulse types seems to be related to the type and content of proteins, being pulse flours with higher protein content exhibiting higher values of viscosity. In addition, it was reported that protein molecules that have affinity for water have the potential to decrease swelling of starch molecules (Shao et al., 2023).

The pastes obtained by heating water dispersions of pulses flours at 7.5% showed in all cases viscoelastic response typical of a weak gel material with the storage modulus (G’) higher than the loss modulus (G’”). However, the values of these modulus varied between pulses and conditions. Decreasing pH and adding calcium influenced differently viscoelastic parameters differently depending on the type of pulse flour, with the effect being more significant at pH 5 with calcium as compared to pH 3 concerning lentil, red lentil and chickpea pastes. For chickpea, lentil and red lentil pastes, the values of G’ and G’” increased when decreasing pH to 5 with and without calcium, but when decreasing pH to 3, the increase in G’ and G’” was lower or not significant compared to the natural condition. For white bean paste, decreasing pH with or without calcium, increased G’ and G’”, with higher effect at pH 3 with calcium.

Pulse gels were obtained when using a concentration of 15% of flour/water and their mechanical properties were compared among pulses and conditions. All the pulses provided self-supporting gels with an elastic character except for white bean gels that showed weaker texture. Variation in mechanical parameters of pulse gels were observed when changing pH and calcium except for white bean. For chickpea, lentil and red lentil, decreasing pH to 3 and adding calcium resulted in less hard and less resistant gel. The observed changes in viscoelastic and mechanical properties of pulse pastes and gels indicate that the acidity and calcium addition did not improve these properties and natural condition can be used to manipulate and to achieve tailored textures of several kinds of food products that requires higher viscosity such as soups or hard texture such as cheese analogues.

The starch swelling and gelatinization phenomena of starch as well as protein aggregation phenomena occurring during the thermomechanical treatment are the main responsible for the viscoelastic and mechanical properties of the flour dispersions (Motta & Zhang, 2019; Pang et al., 2020). After heating, starches change their structure, and form a network. Meanwhile, when heated above their denaturation temperature proteins can aggregate and form a network. Protein
aggregation depends highly on the proteins isoelectric point that vary according to the pulse and in relation to the pH of the medium. At pH close to its isoelectric point that ranges between 4 and 6, proteins aggregate and result in network formation due to their low solubility (Goldstein & Reifen, 2022; Renkema et al., 2002). Accordingly, changes in viscoelastic and mechanical properties of pulse pastes and gels with the different conditions of pH and calcium seems to be related to protein solubility. Nevertheless, findings of this study pointed out relevant differences between flours from white bean and other pulse types, which might be related to the differences in protein types of each pulse.

Building on the findings of the first study that showed the ability of pulse flours to form a consistent gel, the focus of the second study shifted to specifically investigate the mechanical and sensory properties of pulse gels and to gain better understanding about the interaction between pulse flours and other natural ingredients in the development of new solid plant-based products. For this, the changes on mechanical properties of pulse products obtained from chickpea, lentil or red lentil flour when changing the concentration of flour, and sunflower oil, lemon juice, and salt were modelled using regression analysis.

Self-standing gels can be obtained from heated dispersions of pulse flour (lentil, red lentil, and chickpea) at 15% to 17.5% inclusion. Mechanical properties of the three pulse types varied with changes in the concentration of ingredients. Red lentil flour formed gels that were harder, gummier, stiffer, and more resistant to cutting than lentil and chickpea gels. Chickpea gels formed soft and less gummy gels that were less resistant to cutting but were stiffer than lentil gels.

According to the equations obtained from by Response Surface Methodology, it was observed that the effects of changes in the ingredients were different among pulse gels. The equations of each mechanical parameter showed similar pattern for all the pulses regarding the effects of flour and salt content, including a positive quadratic relation with flour and a negative linear relationship with salt. Furthermore, the equations were more complex including interaction effects for red lentil and chickpea. Equations of the red lentil gels showed that the values of mechanical parameters of pulse gels were higher with higher flour, low salt and intermediate concentration of oil. Chickpea gels showed higher values with higher flour, low salt and lower concentration of lemon juice. This indicate that red lentil gels were more sensitive to the oil content in addition to flour and salt, whereas the chickpea gels were more sensitive the lemon juice content in addition to flour and salt.

The flour and salt content had a significant effect on the mechanical properties of all pulses. Hardness, gumminess, stiffness and resistance to penetration and cut of all the studied pulse
gels decreased with salt within the studied range (0% to 1.4%) and increased with flour (15% to 17.5%), respectively. Whereas, oil content affected mainly the red lentil gels. Increasing the oil content increased the hardness, gumminess, stiffness, and resistance of the red lentil gels. Furthermore, the lemon juice content affected the mechanical properties of chickpea. Increasing the lemon content slightly reduced the hardness, gumminess, stiffness, and resistance of chickpea gels. Hence, it should be taken into account the importance of considering the interaction of pulse flour with the other ingredients for achieving the desired in food applications.

The influence of ingredients on the mechanical properties of pulse gels might be explained by the interaction between ingredients and flour components. The formation of self-standing gels based on pulse flours involve mainly the formation of starch-protein network due to starch gelatinization and protein aggregation (Nilsson et al., 2023). Thus, variation in gel properties with different ingredients can be attributed to effect of these ingredients on starches and proteins properties. Accordingly, the higher values of hardness, stiffness, and resistance of gels that were observed with higher flour content could be related to the higher content of starch and proteins that are able to retain more water and strengthening the formed network. Meanwhile the presence of salt decreases the water availability and increase protein solubility, resulting in lower strength of the formed network (Langton et al., 2020). Regarding the increase in hardness, gumminess, stiffness, and resistance of the red lentil gels when increasing oil content, it might be related to the higher emulsifying capacity of red lentil flours as compared to the other pulse types as pointed out in a previous work (Moussaoui et al., 2023). Consequently, it could be suggested that the emulsion particles formed among oil and proteins aggregate due to heating treatments, thus further strengthening the network formed.

For chickpea gels, an important effect of lemon content was observed. Similar trend was observed in previous works that stated a decrease in hardness of chickpea gels due to lemon content (Canet et al., 2015; Dolores Alvarez et al., 2017). This can be attributed to the influence of acidity on both starch and protein. Acidic conditions can lead to the hydrolysis of starch molecules, thus weakening the gel strength (Canet et al., 2015; Hirashima et al., 2012). Furthermore, the solubility of proteins is influenced by pH proximity to their isoelectric point. At pH close to the isoelectric point, protein solubility increases, leading to lower aggregation and a weaker texture (Manassero et al., 2018).

Flash Profile method was used to evaluate how sensory properties of pulse gel products varied with the amount of ingredients (pulse, lemon juice and oil). Participant used different terms in order to describe the sensory differences between samples. Terms related to colour, brightness
and homogeneity were mainly used to describe the appearance of samples. Meanwhile, terms related to texture, such as hardness and gumminess were used. Moreover, terms related to surface properties and to composition were used to describe the texture of pulse gels. Flavour differences among samples included terms related to pulse flavour as well as lemon flavour and other basic tastes such as sour, salty and bitter flavours.

Sensory characteristics of the pulse gels were different according to the type of the pulse flour used. Red lentil gels were described as being homogeneous, creamy, and compact whereas chickpea gels were described as compact but harder. On the other hand, lentil gels were described as rough and sandy. Including oil and lemon in the pulse gels reduced pulse flavours and increased sour taste. Variation among gels elaborated from different pulse flours were basically related to the pulse type. Yamsaengsung et al., (2012) reported that variation in texture properties of plant-based product is mainly due to the different protein and starch composition. In addition, differences in other components of each flour such as polysaccharides and fibres must be taken into consideration as being responsible for differences on texture and flavour of gels. According to our results, changes in sensory characteristics with ingredient reveal the feasibility of modulating the sensory characteristics of pulse-based products in order to elaborate an appealing plant-based product.

Findings from this research topic provide a better conceptual understanding to the wide range of properties obtained by different pulses flours from technological and sensory perspective. Moreover, it underscores the significant effect of the type of the pulse used as well as the effect of the other ingredients and processing conditions on properties of the elaborated pulse-based products. Therefore, the information obtained from this research provides valuable insights for addressing the design and optimization of a new range of plant-based products that are rich in proteins, healthier and more sustainable.
4.1.2 Consumer response to plant-based products

The third and the fourth studies shed the light on the final consumers by investigating their opinions and acceptance of plant-based products. The third study aimed to measure the effect of information about the source of plant-protein and consumers' attitude towards meat reduction on their response to plant-based burgers. The same image of a commercial burger was used with information about the source of plant-protein (soy, pea and seitan (wheat)) as stimulus. Expected liking, emotional response, and healthy, processed and sustainable perception linked to the samples were measured by an online questionnaire. In addition, consumers’ attitude towards meat reduction and other personal traits were registered. Similarly, in the fourth study using an online survey; consumers' attitude towards meat reduction, their food neophilia, and expectations linked to plant-based products were evaluated.

Concerning consumers’ attitude towards meat reduction, new dimensions including hedonic, diet, environment, health, animal suffering and animal sacrifice were re-established. Consumers were segmented into five classes (high supporters, medium supporters, low supporters, partial rejecters and rejecters) based on their attitude towards meat reduction. High supporters were the most in agreement with meat reduction across all the dimensions, whereas rejecters were the most in disagreement with such reduction. In general, high supporters (C5) gave significantly higher scores for all dimensions. Medium supporters (C4) showed a greater difference among dimensions’ mean scores, two points below high supporters (C5) in most dimensions. The low supporters (C3) had significantly lower scores than medium and high supporters (C4 and C5 respectively), giving moderate to high scores for the dimensions of diet, animal sacrifice, environment and health, and lower scores for hedonics and animal suffering. Partial rejecters (C2) gave more importance to the animal sacrifice and health as compared to other dimensions. Rejecters (C1) gave low scores to most dimensions, significantly lower to partial rejecters (C2), except for environment (not significantly different from C2) and health (significantly higher than C2).

Other authors reported that health concerns were behind consumers’ willingness to reduce meat consumption and increase plant-based food consumption (McBey et al., 2019; Sánchez Romero & Ladwein, 2023; Van Vliet et al., 2020). These researchers reported that consumers considered that reducing meat consumption might protect them against various diseases. Environmental concerns had been reported also as an important motivation of consumers to adopt certain meat reduction strategies (Sanchez-Sabate & Sabaté, 2019). Furthermore, previous works suggested that a decrease in meat consumption among consumers was enhanced
by animal welfare consideration (Dagevos & Verbeke, 2022; Perez-Cueto et al., 2022). Additionaly, Giacalone et al., (2022) stated that consumers that gave higher importance to sustainability or health, were more ready to accept plant-based substitutes than those who prioritise flavour.

Previous studies reported that meat attachment was the main driver of consumers’ rejection of meat reduction (Circus & Robison, 2019; Dagevos, 2021; Graça et al., 2015). In addition, less concern by the environment and animal welfare were reported as drivers of rejection of meat reduction among consumers. Nevertheless, it is important to mention that, according to the results of our study, even consumers who rejected meat reduction showed lower reluctance to reduce meat consumption when health concerns were considered. Accordingly, several works pointed out that uncertainty and unfamiliarity, besides of less naturalness, perceived from plant-based product are among the main barriers for consumers to explore meat alternatives (Ford et al., 2023; Hwang et al., 2020; Pohjolainen et al., 2015; Varela et al., 2022). Szenderák et al., (2022) mentioned that omnivore consumers’ associated plant-based diets to negative consequences for their health, such as nutrient deficiencies. From this standpoint, it is important to note that consumers’ inclination to reduce meat consumption and to adopt more plant-based food is a result of a complicated perception process that is influenced by numerous factors including health and environmental concerns, animal welfare and dietary habits. Nonetheless, taste and pleasure linked to meat consumption remain as important factors in consumer decision-making when it comes to meat reduction (Fiorentini et al., 2020; Font-i-Furnols & Guerrero, 2022; Nevalainen et al., 2023).

Within the limits of our study, plant-based burgers were expected to like slightly. The information regarding the source of plant-protein (soy, pea and seitan (wheat)) had no effect on consumers’ expectation of liking, product perception (healthiness, processed and sustainable) and evoked emotions linked to plant-based burgers.

However, expected liking and product perception linked to plant-based burgers highly depended on consumers’ attitude towards meat reduction. Supporters of meat reduction showed high acceptance of plant-based burgers as compared to rejecters of such reduction. Moreover, supporters perceived plant-based burgers as healthier, less processed, and more sustainable, while rejecters showed low acceptance, low healthy and sustainable perception and higher processed perception.
In a recent study, motivations to reduce meat and to adopt meat substitutes, edible insects and cultured meat amongst meat-eating consumers in Australia, China and the UK were investigated. Results revealed differences in motivation among consumers to adopt meat alternatives depending on the source of protein alternative (Ford et al., 2024). Accordingly, it can be suggested that, due to the low variability in plant-based used in this study differences in consumers response might not be captured. Several studies also evaluated consumer perceptions and attitudes towards plant-based food products. For instance, in a study that evaluated Spanish consumers’ attitudes and intentions to purchase plant-based products, authors reported a trend of consumers to adopt moderate attitudes towards plant-based products. In addition, authors reported that consumers’ attitudes affected their purchase intention of plant-based products (Adzran et al., 2024). Similarly, Jaeger et al., (2023) investigated consumers’ intentions regarding plant-based yoghurt and eggs and reported that consumers reacted positively when they were given information on the benefits of plant-based products for their own health and the environment. This, could explain the higher acceptance that supporters showed to plant-based products, as well as their higher perception and healthiness and sustainability. Conversely, Hartmann et al., (2022) evaluated Swiss consumers’ perception of environmental friendliness, healthiness and naturalness of meat and meat substitutes. Authors reported that participants did not perceive meat substitute products as more environmentally friendly than meat, nor considered them as a healthier option. This in accordance with the rejecters’ behaviour observed in our study that did not consider plant-based products as healthier nor sustainable.

Emotional responses evoked by the plant-based burgers varied according to consumers’ attitude towards meat reduction. Samples evoked more positive emotions (happy, secure, and satisfied) in supporters of meat reduction. Meanwhile, the samples evoked negative emotions (disgusted and bored) and the feeling of adventurous in rejecters of meat reduction. The positive emotions were linked to the higher acceptance of plant-based products and higher inclination to adopt meat reduction, whereas negative emotions explained consumers’ rejection of plant-based products for hedonic reasons besides of the uncertainty generated by these products, which was expressed by feelings such as adventurous. Accordingly, the results of this study established a link between consumers’ perception and self-reported emotions which contribute to a better understanding of the hedonic response evoked by plant-based burgers. Similarly, a recent study (Zandstra et al., 2024) investigated evoked emotions by plant-based burgers and meat burgers on Dutch adults (meat eaters and flexitarians). Authors reported that positive
emotions evoked by plant-based burgers were significantly related to the expected liking of plant-based burgers and that choosing a plant-based burger was mainly influenced by being flexitarian (Zandstra et al., 2024). Furthermore, a recent study that evaluated a wide range of commercially available plant-based meat alternatives, indicated that meat-like samples evoked more positive emotions whereas samples that were not perceived to be similar to meat evoked more negative emotion terms (Giezenaar et al., 2024). No differences were registered in the emotional response in terms of the different sources of plant-proteins. This can be associated to the limitation generated from the lack of variability among samples used in this study and to the use of the EsSense 25 lexicon, which is a general lexicon used for different food categories.

After publishing our work, an emotion lexicon specific to meat and plant-based burger patties was established by Orr et al., (2023). In this context, the use of a specific lexicon developed for meat and plant-based burgers might provide deeper insights in consumers’ emotional response towards such kind of products.

Regarding the results obtained from the fourth study, on average, expected liking was rated close to a neutral position (5.46 ± 1.72 on the 9-point hedonic scale), indicating that plant-based burgers were slightly accepted. Mean value of purchase intention was 2.98 ± 1.07 on a 5-point scale, indicating also a neutral willingness of consumers to purchase this type of products.

When segmenting the consumers sample by their attitude towards meat reduction, an important effect of consumer classification was found on expected liking and purchase intention. These results indicate that expected liking and purchase intention of plant-based burgers highly depend on consumers’ attitude towards meat reduction. Significant differences were observed among mean values of expected liking and purchase intention of plant-based burgers according to consumers’ classes as shown in Figure S 4. Consumers more supportive (S3) of meat reduction gave significantly higher scores on liking and purchase intention as compared to intermediate (S2) and to less (S1) supporting classes.

A significant effect of the level of food neophilia of consumers on the expected liking and purchase intention of plant-based burgers was found. However, there was no effect of the source of plant-protein (soy, pea or wheat (seitan). In addition, significant differences on expected liking and purchase intention of plant-based burgers were found according to consumers’ classification based on food neophilia, as shown in Figure S 5. Consumers that were more neophilic (N3) gave significantly higher values to the plant-based burgers in terms of the expected liking as compared to the intermediate (N2) and less (N1) neophilic groups of consumers. Moreover, consumers from the intermediate neophilic level (N2) gave significantly
higher values of the expected liking elicited by the plant-based burgers as compared to consumers from the low neophilia group (N1). Regarding purchase intention, consumers that were more neophilic (N3) were more willing to purchase the plant-based burgers than the intermediate (N2) and low (N1) neophilia groups. However no significant differences were observed between intermediate (N2) and low (N1) neophilia groups.

After that, the reliability analysis results indicated that Cronbach’s alpha for each of the four dimensions of the attitude towards meat reduction measurements exceeded 0.8, demonstrating good internal consistency for each dimension (Table S2). Further, the results from the CFA analysis showed that all the observed variables (scale items) significantly loaded on their underlying latent construct (all p-values < 0.001), and the standardized regression weights indicated satisfactory factor loadings. Additionally, the goodness-of-fit measures from the CFA analysis were favourable: CMIN= 155.18(82), p < 0.001, CMIN/DF=1.89, GFI=0.95, CFI=0.98, RMSEA=0.50. These metrics confirm the factors, indicating that the scale items adequately fit the model and measure with validity consumers’ attitude towards meat reduction.

Finally, Structural Equation Modelling (SEM) was employed to test the postulated conceptual framework in Figure 9. The SEM assessed the effect of the various dimensions included in the measurement of attitude towards meat reduction (i.e environment, health, diet and ethics) and the effect of food neophilia and sociodemographic traits on consumers’ expected liking and purchase intention of plant-based products. The resulting structural model showed satisfactory overall fit: CMIN=770.73(389), p < 0.001, CMIN/DF= 1.98; GFI=0.88; CFI=0.94; RMSEA=0.05, with all path estimates being significant (Figure S6).

As shown in Figure S6, the effect of environment (β = 0.544, p < 0.001) and diet (β = 0.167, p = 0.022) motivations to reduce meat consumption positively affected ethical consciousness, indicating that participants motivated by environmental and dietary factors tend to have a higher ethical consciousness regarding animal welfare.

Ethical concerns positively affected both expected liking (β = 0.418, p < 0.001) and purchase intention (β = 0.105, p = 0.024) of plant-based products. As Ethical dimension is based on concerns on animal welfare, this result suggest that participants concerned by animal welfare show higher expected liking and intent to purchase plant-based products. Moreover, a strong relationship was observed between expected liking and purchase intention of plant-based products (β = 0.730, p < 0.001).
Food neophilia, affected positively the expected liking of plant–based products ($\beta = 0.293$, p < 0.001), showing that participants more willing-to-try new food had higher liking expectations towards plant-based options. Similar findings were reported in a recent study that stated a negative correlation between food neophobia and the acceptance of new plant-based products that are considered as sustainable (Noemi et al., 2024).

However, health concerns did not show a significant effect on the measured variables. In a previous study (Moussaoui et al., 2023), it was found that consumers rejecting the reduction of meat consumption were less reluctant to such reduction when considering its effect on health. The latter research also showed that health perception was relatively associated to processed perception of the same stimuli for rejecters of meat reduction. It was also found that health concerns were important factors for supporters of meat reduction. Therefore, it seems that health concerns motivate both supporters and rejecters to adopt meat reduction. This could be a potential reason for a not significant effect of health on the attitude towards meat reduction. More research is needed to understand health construct and its role in consumers’ perception and attitude towards meat reduction.

Regarding consumers’ diet, it had a significant effect on both expected liking ($\beta = 0.164$, p < 0.001) and purchase intention ($\beta = 0.125$, p < 0.001) of plant-based products. Similarly, previous works reported differences in food choice motivations and the importance of reducing meat intake between consumers according to their diet. Accordingly, consumers who consider their selves as vegan, vegetarian or flexitarians were reported as the most in agreement with adopting more plant-based diet and reducing meat intake. Meanwhile, consumers who identify their selves as omnivores were showed less reluctance to adopt more plant-based products in their diet (De Boer et al., 2017; Noemi et al., 2024; Sheen et al., 2023)

Consumers' classification according to their attitude towards meat reduction and the food neophilia level helped to understand the most important factors driving consumers’ preferences and perception of plant-based products. These findings may help food industry and policymakers in the development of new plant-based products that meet consumers’ preferences and to adopt effective strategies to encourage consumers to embrace more plant-based products in their diets.
4.2. Conclusions

The mains conclusions derived from this thesis can be summarized as follows:

- Pulses flours as source of protein ingredients exhibit a wide range of techno-functional properties that can be modulated by varying the type of pulse, the pH and the ionic strength to produce new plant-based food with tailored characteristics.

- All pulse flours are good emulsifiers. In addition, white bean flour provides a high water holding capacity, while lentil and red lentil flours are good as foaming ingredients. Chickpea flour exhibit high thickening capacity while red lentil exhibit high gelation capacity. Lowering pH and adding calcium increases water holding, foaming and thickening capacities, while it decreases emulsifying and gelation capacities.

- The self-standing gels obtained from heated dispersions of pulse flour (lentil, red lentil and chickpea) can be the base of new plant-based solid products whose mechanical and sensory properties are modulated by other natural ingredients such as oil, lemon juice and salt.

- Red lentil produces pink products with a homogeneous, creamy and compact texture that melt in the mouth. Chickpea provides compact products that are harder and have more chickpea flavour, while lentil provides gels that have a sandy texture and with more intense pulse flavour. The intensity of pulse flavour products is reduced when including oil and lemon. Hardness of lentil and red lentil products increases when including oil.

- The willingness to reduce meat in diet of consumers is mainly driven by health, environmental and animal welfare concerns while pleasure and habits associated to meat consumption are the main barriers to such reduction. Five groups of consumers were identified according to their attitude towards meat reduction: high supporters, medium supporters, low supporters, partial rejecters or rejecters.

- The information regarding the source of plant-protein (soy, pea and seitan (wheat)) had no effect on consumers’ expectation of liking product perception (healthiness, processed and sustainable) and evoked emotions linked to plant-based burgers. However, expected liking, product perception and emotions linked to plant-based burgers highly depended on the consumers’ attitude towards meat reduction. For medium and high supporters, plant-based burgers were expected to like more and evoked positive emotions. In addition, medium and high supporters considered plant-based burgers as healthier and more sustainable. Meanwhile, plant-based burgers were expected to be less liked and
evoking negative emotions on rejecters of meat reduction who perceived them as more processed.

- Individual consumers’ traits (attitude towards meat reduction, food neophilia and diet) had a significant effect on the expected liking and purchase intention of plant-based burgers.

- Young Spanish consumers concerns about environment, health and dietary habits related to meat consumption can be influenced by ethical concerns related to animal welfare, thus driving their expected liking and purchase intention of plant-based products. Thus, encouraging Spanish consumers’ ethical concerns can be considered for promoting the adoption of more plant-based diets.

### 4.3. Future Research Lines

This thesis had the goal of expanding the knowledge about the potential of pulse flours for the development of novel plant-based food and to determine consumers’ response towards such kind of products. This research delved into examining the physicochemical and sensory characteristics of pulse flours and products, and to examine the effect of the information and the attitude towards meat reduction on consumers’ response to plant-based products. Likewise, potential future research could explore the differences on qualitative components of pulse flours, including protein and starch as well as their changes under different processing conditions in order to predict and control product quality during the processing treatments. In addition, future studies are required for the optimization of pulse-based products considering consumer opinions in order to design products with sensory properties that maximize consumer acceptance. Further, given the fact that these products combine health advantages and address sustainability concerns, future studies might examine the nutritional profile of these products in order to facilitate addressing their health benefits and attracting consumers that are seeking for nutrient dense food options. Moreover, considering the sustainability regarding the efficiency and waste related to pulse-based production process, would be interesting for future investigations.

The strong effect of consumers’ classification according to the attitude towards meat reduction on their response to plant-based products could potentially mask other effects, such as the source of plant-protein. Moreover, this research has not included a meat burger options to compare the effect of animal- versus plant-based burgers. Thus, it would be interesting to
include animal-based products in future studies to contrast the robustness of the consumers’ classification approach used in this thesis.

In addition, consumers’ perception of the different plant-based products reported by means of an online questionnaire is not necessarily the same when tasting the real product. Both approaches (expectations versus real experience with tasting) should be compared in future studies in order to determine whether the exposure to the sensory attributes of the products influences or adjusts the expectations, predominantly driven by consumers' attitudes towards meat reduction in this research. Given the expected potential increase in availability and variability of new plant-based products, the effect of other consumers’ traits such as cultural origin, age, education level and gender on consumers’ willingness to reduce meat consumption could also be explored in future works.
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6. Annex I
1. Supplementary Figures Study 2

**Figure S1.** Hardness of red lentil gels as a function of flour, salt and oil concentrations (Model equations are shown in Table 12, probability for entry and for removal equal to 0.05).
Figure S2. Hardness of chickpea gels as a function of flour, lemon and oil concentrations (Model equations are shown in Table 12, probability for entry and for removal equal to 0.05)

Figure S3. Young Modulus of chickpea gels as a function of flour, lemon and oil concentrations (Model equations are shown in Table 12, probability for entry and for removal equal to 0.05).
2. Supplementary Table Study 3

Table S1. Frequency counts of discriminant emotions that did not meet theoretical frequencies requirement for Chi-square test.

<table>
<thead>
<tr>
<th>Emotion terms</th>
<th>C1 (Rejecters)</th>
<th>C2 (Partial rejecters)</th>
<th>C3 (Low supporters)</th>
<th>C4 (Medium supporters)</th>
<th>C5 (High supporters)</th>
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<tr>
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<td>1</td>
<td>0</td>
<td>0</td>
<td>7</td>
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<tr>
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<td>3</td>
<td>4</td>
<td>0</td>
<td>0</td>
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<td>Nostalgic</td>
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<td>3</td>
<td>2</td>
<td>3</td>
<td>0</td>
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<tr>
<td>Wild</td>
<td>17</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Guilty</td>
<td>15</td>
<td>4</td>
<td>2</td>
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<td>0</td>
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3. Supplementary Tables and Figures Study 4

**Figure S 4.** Mean values of expected liking and purchase intention of plant-based burgers according to consumers’ classes. Different letters within the same variable indicate significant differences between consumer classes according to Tukey's test at the level alpha=0.05. S1: Class of consumers less supportive of meat reduction; S2: Class of consumers intermediate supportive of meat reduction; S3: Class of consumers most supportive of meat reduction.

**Figure S 5.** Mean values of expected liking and purchase intention of plant-based burgers according to consumers’ food neophilia. Different letters within the same variable indicate significant differences between consumer classes according to Tukey's test at the level alpha=0.05. N1: Consumers less neophilic; N2: Consumers moderately neophilic; N3: Consumers more neophilic.
**Figure S 6.** Results of Structural Equation Modelling (SEM) Analysis. In the model, β’s are regression weights, φ’s are correlation coefficients. All the regression are weights significant at p<0.001, except for βHLT with p = 0.976.

**Table S 2.** Results of the Reliability and Confirmatory Factor Analysis assessed on the items within each dimension included in the attitude towards meat reduction scale.

<table>
<thead>
<tr>
<th>Measures</th>
<th>M</th>
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<th>α</th>
<th>FL</th>
<th>CR</th>
<th>AVE</th>
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M – Mean; SD – Standard Deviation; α – Cronbach’s alpha issued from the reliability Analysis. FL – Factor Loading; CR – Composite Reliability; AVE – Average Variance Extracted issued from the Confirmatory Analysis.