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COMPREHENSIVE REVIEW

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Legume byproducts as ingredients for food applications: Preparation, nutrition, bioactivity, and techno-functional properties

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Abstract

The demand for high-quality alternative food proteins has increased over the last few decades due to nutritional and environmental concerns, leading to the growing consumption of legumes such as common bean, chickpea, lentil, lupin, and pea. However, this has also increased the quantity of non-utilized byproducts (such as seed coats, pods, broken seeds, and wastewaters) that could be exploited as sources of ingredients and bioactive compounds in a circular economy. This review focuses on the incorporation of legume byproducts into foods when they are formulated as flours, protein/fiber or solid/liquid fractions, or biological extracts and uses an analytical approach to identify their nutritional, health-promoting, and techno-functional properties. Correlation-based network analysis of nutritional, technological, and sensory characteristics was used to explore the potential of legume byproducts in food products in a systematic manner. Flour is the most widely used legume-based food ingredient and is present at levels of 2%–30% in bakery products, but purified fractions and extracts should be investigated in more detail. Health beverages and vegan dressings with an extended shelf-life are promising applications thanks to the techno-functional features of legume byproducts (e.g., foaming and emulsifying behaviors) and the presence of polyphenols. A deeper exploration of eco-friendly processing techniques (e.g., fermentation and ohmic treatment) is necessary to improve the techno-functional properties of ingredients and the sensory characteristics of foods in a sustainable manner. The processing of legume byproducts combined with improved legume genetic resources could enhance the nutritional, functional, and technological properties of ingredients to ensure that legume-based foods achieve wider industrial and consumer acceptance.

KEYWORDS
bioactive compounds, food ingredients, functional foods, plant-based protein, pulse genetic resources, waste recovery

1 | INTRODUCTION

The conservation of food-legume genetic diversity and its exploitation in food production will increase the sustainability of agriculture and the availability of healthier food products (Bellucci et al., 2021). In 2019, the Intergovernmental Panel on Climate Change report entitled "Climate Change and Land" (IPCC, 2019) indicated that the transition to novel plant-based diets could "…present major opportunities for adaptation and mitigation while generating significant co-benefits in terms of human health…" Indeed, there is a great demand for sustainable plant-based foods and ingredients that provide health benefits (Wild et al., 2014). Legumes are major staples in many countries and provide an inexpensive source of proteins, dietary fiber, vitamins, minerals, and bioactive compounds (Rebello et al., 2014). The term "legume" can refer to any tissues from plants of the family Fabaceae (nom. alt. Leguminosae), whereas pulses refer specifically to the edible seeds (Capurso et al., 2018). Increasing awareness of legume-based food, particularly the health and environmental benefits, has resulted in a shift toward legumes as healthy alternatives. However, the expanded utilization of legumes has also increased the amount of food waste generated in the value chain, such as seed pods, leaves, and wastewater (Tassoni et al., 2020).

Legume splitting followed by seed coat and pod removal is common practice in the production chain because split legumes are popular products in many markets (Sun et al., 2020). Byproducts generated during legume processing can exceed 25% of the total biomass (Tassoni et al., 2020). The reprocessing of food waste and byproducts provides environmental, economic, and nutritional benefits, but sustainability is challenging (S. Kumar et al., 2017). Pulse byproducts also contain a high content of polyphenols, protein, dietary fiber, and other important nutritional components (Sun et al., 2020). For example, previous studies have shown that the seed coat's total phenolic content (TPC) is strongly associated with health-promoting antioxidant activity (Zhang et al., 2015). Therefore, in the circular economy, legume byproducts may provide an important source of nutritional and techno-functionally valuable food ingredients (Osorio et al., 2021). For example, pomace, seeds, hulls, and peels are useful as ingredients in pulse-based snacks (Escobedo & Mojica, 2021), noodles, sports drinks, ice creams, and biscuits, among others (B. K. Tiwari et al., 2020).

The inclusion of functional food ingredients may alter the composition of components such as protein and dietary fiber in the final product and can also affect technological properties such as emulsification, foaming, gelation (Godswill et al., 2019), hardness, chewiness, springiness, and overall consumer acceptance (Machado & Thys, 2019). The techno-functional evaluation of ingredients derived from pulse waste may help to predict the behavior and overall quality of the final food product (Godswill et al., 2019). In addition, the smell, taste, and texture of the final food products must be assessed in consumer tests to ensure sensorial acceptance (Lawless & Heymann, 2010).

Here, we discuss the potential of legume byproducts as food ingredients (flour, fractions, or extracts) by systematically reviewing the nutritional value, bioactive and antinutritional composition, health properties, and especially techno-functional parameters of different legume waste products (seed coats, husks, hulls, pods, and wastewaters). We include the common bean (dry seed or fresh green bean, *Phaseolus vulgaris* L.), chickpea (*Cicer arietinum*), lupin (*Lupinus* spp.), pea (fresh or dry yellow peas, *Pisum sativum*), fava or broad bean (*Vicia fabae*), and lentil (*Lens culinaris*) as the legume crops most widely grown for human consumption. Finally, we consider the nutritional, techno-functional, and sensory properties of legume byproducts (flours, fractions, and extracts) in recently developed food products.

2 | LITERATURE SEARCH STRATEGY, ELIGIBILITY CRITERIA, AND DATA ELABORATION

We screened online databases such as Scopus, Google Scholar, and Science Direct using combinations of the keywords legume byproducts, pulse byproducts, food application, functional food, food ingredients, and bioactive compounds. Byproducts from soybean, feed applications, and articles published before 2010 were excluded. Although soybean is a legume, it is also an oilseed and is primarily processed for this purpose (Schneider, 2002). Moreover, soybean is a widely used protein source, and excess consumption can lead to food allergies (Alok Kumar Verma et al., 2013). We used a hierarchical approach based on the title, abstract, and manuscript text to select articles dealing with food applications of pods, seed coats/husk/hulls, broken seeds, wastewater, and minor waste products

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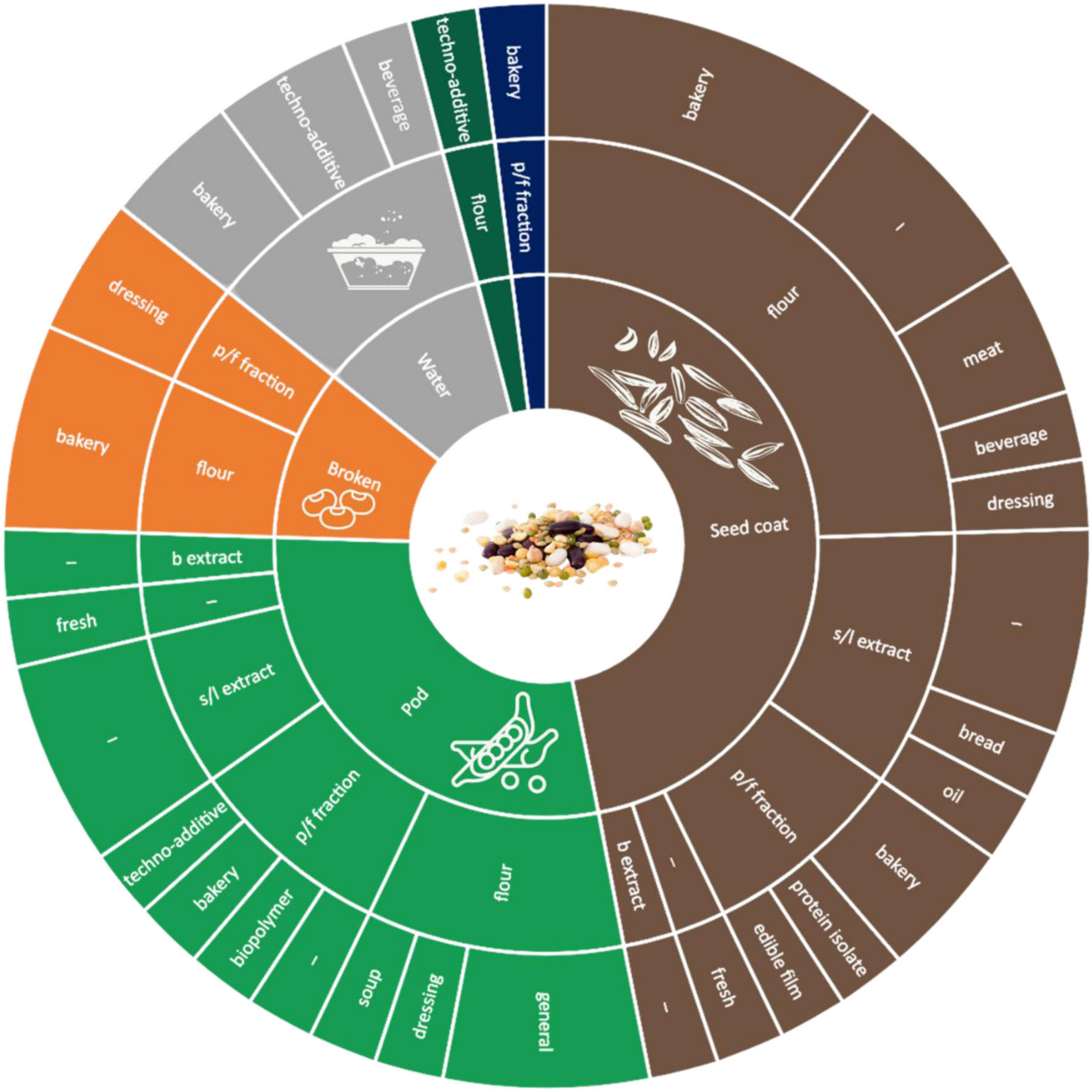

FIGURE 1 Graphical representation of reviewed articles (2010–2022), showing the transformation of legume byproducts to ingredients and food applications. The inclusion criteria of the articles were year of publication (2010–2022), food application, and potential ingredients for food application from legume byproducts. The exclusion criteria were feed application, review articles, soybean byproducts. Abbreviations: s/l, solid/liquid; p/f, protein/fiber; b, biological; "–": no food application developed. Meat means meat products enriched with legume byproducts.

(okara and bagasse). Research papers with innovative solutions at technology readiness levels (TRLs) of 2–5 were included. Thus, we considered articles characterizing and studying the properties of legume byproducts as ingredients (flours, extracts and fractions) in foods (TRL2–3) and articles developing laboratory-scale foods (TRL4) or prototype legume byproducts as ingredients (TRL5). We found 49 relevant articles (Figure 1).

A database was established to extract information concerning (1) the nutritional, bioactive, antinutrient, health-promoting, and techno-functional properties of legume byproducts/ingredients and (2) the nutritional, techno-functional, and sensorial properties of any resulting food applications. Ingredients based on legume byproducts or foods made from them were classified, and the values of selected properties were expressed and/or transformed according to the most common unit of measurement, whenever possible. For food products at different enrichment levels, the mean value was calculated. In Figures 1 and 2, the reviewed articles are classified and presented as a sunburst chart and a free graphical representation, respectively. Figure 3 presents data from research articles about foods including legume byproducts/ingredients. The data from Tables 1 and 2 were used for nutritional properties, Table 4 for rheological behavior, and Table 5 for sensorial parameters evaluated on a 9-point scale. These data were used to make a correlation graph (Figure 3).

2.1 | Description of correlation-based network statistical analysis

All features used for the correlation analysis (Figure 3) were represented by the same unit within the group of nutritional, techno-functional, and sensory parameters. Pearson's correlation matrices were calculated in Metaboanalyst 5.0. We used a *p*-value threshold of .05. The most meaningful correlations were selected with arbitrary cutoffs to an absolute correlation coefficient > 0.3. This relatively relaxed threshold was used because data were integrated from different platforms. Depending on the dataset, we used different numbers of replicates for the different parameters (3–25 for nutritional features, 11–28 for techno-functional parameters, and 9–25 for sensorial characteristics).

3 | LEGUME BYPRODUCTS FOR FOOD APPLICATIONS

Legumes are staple foods in many countries. Common bean, chickpea, lupin, pea, fava or broad bean, and lentil account for 80% of the world's production of pulses (Faostat, 2022). However, up to 25% of the product is wasted, reflecting a combination of non-compliant beans (density, size, or appearance), broken beans, and the pods, leaves, and stems that are discarded during processing. The field residues are pods, husks, leaves, and bagasse, whereas processing waste (generated during drying, milling, dehulling, and sorting) includes seed coats, fresh hulls, broken seeds, and cooking/soaking water from the canning process (Tassoni et al., 2020).

Pulses are consumed in the form of dehulled split pulses, so the milling industry usually removes the husk/hull and splits the seeds. The dehulling process is responsible for the large quantity of wasted splits, ground flours, and other fractionated proteins and fibers. Broken beans (~0.025% of the total) are often discarded (Campos-Vega et al., 2020). Bean hulls represent 7%–13% of the seed, and the equivalent value of pea and lentil is ~8%. The blend of hulls, cotyledon, broken pieces, and flour (rich in starch and protein) can reach 10%–21% of the total (Oomah et al., 2011). In lupin, the seed coat represents ~25% of the seed and in chickpea up to 28% (Zhong et al., 2018). Pea pods represent 30%–67% of the total weight of the whole pod (Varzakas et al., 2016), and this value is ~70% for broad beans (Campos-Vega et al., 2020) and 39% for common beans (Martínez-Castaño et al., 2020). Another interesting but overlooked residue is the okara, the pomace generated by milk extraction (Lian et al., 2020). The water cooking residue is a viscous, semi-transparent liquid produced when pulses are boiled in water while soaking liquid is left after the soaking process typical for legume consumption, which reduces the quantity of macronutrients (i.e., water-soluble proteins) and phytochemicals in the seeds (Huang et al., 2017).

In 2020, 90 million tons of pulses were produced globally, of which beans (dry and string bean) accounted for 32%, followed by chickpeas (17%), dry peas (16%), broad beans (6%), lentils (7%), lupins (1%), and others (Faostat, 2022). Figure 1 shows the different types of waste generated at different stages of production (seed coats, husks, hulls, pods, water, broken seeds, okara, and bagasse). The most widely studied varieties in the selected food applications are chickpea (~30% of selected articles), pea (~20%), bean (dry and string bean, 20%), broad bean (15%), lupin, lentil (5%), and others (10%) including mung bean (*Vigna radiata*), moth bean (*V. aconitifolia*), and cowpea (*V. unguiculata*). Lentil production rose to ~6.3 million tons globally in 2022 (Faostat, 2022), but lentil byproducts have limited food applications. Stantiall et al. (2018) and Ricci et al. (2018) successfully developed biopolymers and food additives from lentil byproducts.

4 | PREPARATION OF BY-PRODUCT AS FOOD INGREDIENTS

The treatments and preparations used to stabilize legume byproducts as food ingredients can affect both the bioactive components (e.g., dietary fiber and phenols) and the technological properties because they are strictly related. The main formulations (Figure 1) used for food enrichment include flours, physical extracts, solid/liquid extracts, and biological extracts from processes such as enzyme treatment and fermentation.

4.1 | Flour

Legume byproducts are mainly derived from seed coats (dry), pods (wet), and broken seeds (dry) that require further processing. The pre-treatment of byproducts (i.e., soaking, sieve fractionation, blanching, roasting, boiling, pre-gelatinization), as well as the drying (temperature and time), grinding (sieve mesh), and storage conditions, may affect the chemical composition, nutritional, and functional properties of the resulting flour. Flours are used in bakery products with different characteristics such as leavened foods (bread, cakes), deep-fried snacks, baked products (crackers, cookies), beverages, meat products, and dressings.

For broken seeds, soaking and cooking may be necessary for the function of the targeted food, especially to eliminate antinutritional factors such as phytic acid (Escobedo & Mojica, 2021). To produce gluten-free instant pasta from carioca bean, seeds were soaked for 6 h and cooked for 15 min at 121°C to produce pre-gelatinized flours (Bento et al., 2021). Cookies were made from broken common beans soaked in hot water (40°C) for 4 h (Bassinello et al., 2011). The soaking step could be omitted as demonstrated by Carvalho et al. (2012) for a broken common bean-based snack. Bento et al. (2021) concluded that soaking byproducts affect the technological properties of pre-gelatinized flours enabling their use in instant pasta. Non-macerated byproduct flours were suitable as ingredients for baked snacks.

For wet tissues such as pods, the preparation of flours starts with a blanching step to inactivate microorganisms and enzymes. Pea pods were blanched for 2–10 min at 95–100°C (Hanan et al., 2020; Rudra et al., 2020), whereas common bean pods were disinfected with polyhexamethylene biguanide rather than blanching (Martínez-Castaño et al., 2020). Chickpea byproducts were soaked for 1 h and then blanched (Chakraborty et al., 2022) for beverage applications or boiled for 10 min (Beniwal & Jood, 2015). After blanching, the water is removed by air drying, usually at 42–60°C for 3–8 h. Martínez-Castaño et al. (2020) compared vacuum drying with air dying at 60°C for 8 h. The study revealed that the color, water-holding capacity, and oil-holding capacity were similar for both methods, except for the antioxidant levels. The authors recommended convection drying as a more economical and available process than vacuum drying.

Pre-treated byproducts (or the dried husk, hull, or seed coat) are typically ground in millers followed by sieving through a mesh rating of 35–60 (corresponding to 250–500 μm). In some cases, sieve fractionation is carried out before final grinding to separate protein-rich fractions as shown for moth bean byproducts (Kamani et al., 2020). Grinding and particle size affect the technological properties of the flour such as water-holding capacity, which is the amount of water absorbed per gram of flour. This is also known as the water-binding capacity or water-absorption capacity (WAC), although the measurement methods may differ (Boye et al., 2010). For fruit and vegetable byproducts, Santos et al. (2022) recommended a 0.5 mm particle size for optimal hydration properties. WAC depends on hydrophilic components such as insoluble dietary fiber (IDF), which is abundant in pulse byproducts (Boye et al., 2010). The WAC is higher for smaller particles to a lower limit of 1.1–0.55 mm because the surface area and pore volume increase. Nevertheless, the hydration properties decline with a particle size lower than 0.5 mm probably due to the dietary fiber composition (Santos et al., 2022). The ratio of soluble dietary fiber (SDF) to IDF (SDF/IDF) increases at lower particle sizes and reflects the lower hydration properties as the proportion of insoluble fiber decreases (Esposito et al., 2005). In pea hulls, water retention and absorption increased when the particle size dropped from 0.95 to 0.3 mm but decreased for smaller particles. Below a particle size of 0.5 mm, the antioxidant activity of flours increased (Esposito et al., 2005). The particle size of flour is an important parameter affecting not only the hydration properties but also the recovery of bioactive compounds. This should be considered when preparing flours because the grinding conditions are not always mentioned. The particle size of flours ranged from 0.1 to 2 mm in the reviewed articles, but 0.25–0.50 mm was the most common range.

Flour can also be obtained also from chickpea okara after milk extraction (Lian et al., 2020), which takes place after soaking, drying, and grinding. This residue has been investigated in only a few studies, and with new vegan market segments, it could be valorized once higher quantities are available. In conclusion, pre-treatments for flour preparation can affect macronutrients and micronutrients responsible for the nutritional and technological properties of legume byproducts.

4.2 | Protein and fiber fractions

There is increasing interest in the fractionation of pulses into their components such as proteins and fibers (Espinosa-Ramírez & Serna-Saldívar, 2019). Once they are separated, they can be used as ingredients in many other formulations (Tassoni et al., 2020). Extraction may also help to lower the content of undesirable compounds (Section 5.5). Protein and starch/fiber components can be separated by dry methods such as air classification, or wet methods such as conventional/water extraction, alkaline extraction/isoelectric precipitation, and enzymatic treatment (Vogelsang-O'Dwyer et al., 2021). Air classification consists of milling pulses into flours with two different particle sizes and densities, separating the protein-rich fine fraction from the starch-rich coarse fraction (Boye et al., 2010). The conventional wet method used to separate proteins and fibers is the milling of raw material and homogenization in water, then the liquid (rich in proteins) is separated from the residue (rich in fibers) by filtration or centrifugation. Belghith-Fendri et al. (2016a) applied this method to pods, and the extracted fibers were later used to enrich bread. Modifications of the conventional wet method may involve the use of chemicals (alkali and acids), enzymes (e.g., amylases and proteases), salts, and membranes.

Chemical treatment takes advantage of the pH-dependent solubility of pulse proteins. The most widely used method consists of two steps: alkaline extraction and isoelectric precipitation. Briefly, proteins are solubilized by adding sodium hydroxide to achieve a pH of 8–10 (high protein solubility), whereas the fibers tend to precipitate. Later, hydrochloric acid is added to achieve a pH of 4–4.5, at which pulse proteins are least soluble (isoelectric point), allowing their recovery following precipitation (Boye et al., 2010). This method requires harsh conditions that achieve high yields at the expense of ingredient functionality. Abdel-Haleem et al. (2022) and De La Rosa-MilÍan et al. (2017) applied this method to obtain protein isolates and bagasse (as byproducts of the protein extraction process). Milder chemical treatments are also available, such as the treatment of legume byproducts with a neutral phosphate buffer for 3 h while stirring at room temperature (Prandi et al., 2021). The liquid protein-rich fraction can then be separated from the solid fiber-rich fraction using a decanter, resulting in a highly pure protein fraction with good functional properties, despite the low extract yield.

Enzymes can be used to obtain purer ingredients based on proteins (Prandi et al., 2021) and fibers (Niño-Medina et al., 2019; Urias-Orona et al., 2010). Amylases and/or proteases are added to the material and dispersed into a solution for starch and protein degradation. Optimal temperature and pH conditions are adjusted according to the enzymes used. The supernatant is collected and dried after the treatment period (Ozturk et al., 2021). This method was used by Urias-Orona et al. (2010) to obtain pectin with good antioxidant activity from chickpea husk, which was used to create a fiber-enriched bread (Niño-Medina et al., 2019). Prandi et al. (2021) stated that enzymatic treatment produces a mixture of amino acids and highly digestible peptides.

The utilization of salts for salt extraction or micellization can also produce protein and fiber fractions. This technique is based on the addition of an appropriate salt solution to extract proteins (salting-in) and remove insoluble fibers, before diluting the protein extract (salting-out) to induce protein precipitation and facilitate protein recovery (Boye et al., 2010). None of the reviewed articles employed this method. However, Ricci et al. (2018) extracted proteins from legume byproducts by salt extraction followed by ultrafiltration (as an alternative to isoelectric precipitation) with the aim of producing bioplastics. Ultrafiltration utilizes specific molecular weight cut-off membranes, which isolate the proteins of interest while releasing the non-proteinaceous components. Protein analysis revealed mainly the presence of globulins (salt-soluble fraction), which are the major storage proteins in legumes. This implies that the final ingredients may be characterized by different techno-functional properties, compared to those obtained using other methods.

In conclusion, many techniques are available to extract protein and fiber fractions from legume byproducts. However, it is important to consider not only the time and cost of the treatment but also the properties of the final product, such as yield, degree of purity, and physical and techno-functional characteristics (Loveday, 2019).

4.3 | Extracts

Extracts (solid/liquid, liquid/liquid, and biological) usually target the bioactive compounds of byproducts used as ingredients to improve the nutritional, sensory, and technological properties of conventional foods/functional foods, nutraceuticals, films/gels for bioactive food packaging and others (Lemes et al., 2022). The main bioactive compounds for food applications are bioactive peptides, phenolic compounds, carbohydrates, and other molecules such as carotenoids responsible for antioxidant and antibacterial effects.

4.3.1 | Solid/liquid extracts

Conventional solid/liquid extraction combines operations such as maceration, homogenization, stirring, heating, separation (centrifugation, filtration), and stabilization (freeze-drying, drying, or cold storage) and further processing for food applications (encapsulation). The latter is important because direct mixing should be avoided, considering the sensitivity of these bioactive compounds (e.g., to light, oxygen, moisture, pH, and heating) and sensorial implications such as the astringency of polyphenols, which could affect the taste and smell of food products (Comunian et al., 2021).

The solvent determines the selectivity of extraction. Generally, organic solvents are suitable for liposoluble compounds, whereas water and hydroalcoholic solutions are recommended for polar compounds. Among the reviewed articles, the solvents used to prepare bioactive extracts included water, ethanol, methanol, and hydroalcoholic mixtures (70%–90% methanol or ethanol). Eco-friendly and food-grade solvents are required for food applications. The nature of the solvent also influences the extract quality as does the extraction method (e.g., ultrasound, pressurized liquid, and microwave-assisted). Eco-friendly techniques and solvents could be an alternative to conventional heating processes, which can degrade bioactive compounds. For instance, ohmic heating technology

(Coelho et al., 2019) gave good results for carotenoids and polyphenols in tomato byproducts. In the reviewed articles, ultrasound-assisted extraction was applied to broad beans (Abu-Reidah et al., 2017) for metabolite profiling to cowpea pods for the extraction of phenolic compounds (Traffano-Schiffo et al., 2020) and to common bean pods to explore the antiadhesive activity of hydroethanolic extracts (Popowski et al., 2021). Most of the extracts were prepared by conventional extraction such as stirring for up to 24 h at room temperature or higher (i.e., hot water at 80°C), followed by centrifugation or filtration, followed by cold storage, drying or freeze drying. To the best of our knowledge, ohmic treatment has not been applied to legume byproducts, although it has been evaluated in pulses. Most studies characterized the extracts, highlighting their potential use as food preservatives, natural antioxidants, and technological additives, but only a few food applications were implemented. Freeze-dried powder from whole black bean (*P. vulgaris* L. var.) seed coats was extracted at 27°C with 60% (v/v) ethanol in water acidified with 0.1% acetic acid for 4 h, filtered and concentrated at 50°C, lyophilized, and mixed with wheat flour to produce a bread enriched with flavonoids and saponins (Chávez-Santoscoy et al., 2016). Barakat et al. (2017) used broad bean seed coats as a source to produce antioxidants for oil. As an extra processing step to protect bioactivity, Traffano-Schiffo et al. (2020) encapsulated cowpea pod extracts in Ca (II)-alginate beads with the addition of Arabic or guar gums or cowpea isolated proteins to produce a hydrogel for techno-functional foods. Stabilized or encapsulated solid/liquid extracts provide an easy-to-use ingredient for innovative food formulations.

4.3.2 | Biological extracts

Biological processes such as enzymatic digestion and fermentation provide purer extracts with a lower toxicity and environmental impact as a valuable option for agro-industrial waste valorization (Lemes et al., 2022). Fermentation is therefore suitable for the transformation of pulse byproducts into functional ingredients. Moreover, fermentation can reduce the content of antinutrients while increasing the bioavailability of bioactive compounds (Y. Kumar et al., 2021).

To the best of our knowledge, few studies have investigated the fermentation of pulse byproducts. Anbuselvi et al. (2014) and Zuluaga et al. (2020) explored the use of *Saccharomyces cerevisiae* to produce extracts of single-cell protein and bioactive carbohydrates (cyclitols), respectively. In addition, R. Sharma and Ghoshal (2020) investigated the production of carotenoid extracts starting from the fermentation of mung bean husks and pea pods by *Rhodotorula mucilaginosa*. In conclusion, the application of bioactive extracts in food is limited and more eco-friendly technologies such as ohmic treatment or fermentation should be considered to facilitate extraction and improve sustainability.

5 | NUTRITIONAL AND BIOACTIVE PROPERTIES

The formulation of foods with legume byproducts aims to modify the techno-functional properties of conventional formulations, thus valorizing byproducts in a sustainable manner. The nutritional composition of the main ingredients and final foods are summarized in Table 1. The nutritional composition of legume byproducts in foods varies substantially, including protein (1.50%–24.91%), dietary fiber (3.15%–21.70%), and lipids (0.03%–33.72%). The trend in pulse-based snacks is to increase protein and dietary fiber levels while decreasing the lipid content, but this is difficult to achieve (Escobedo & Mojica, 2021) and the same can be implied for legume byproducts in foods. Protein and dietary fiber as macronutrients increase the nutritional value of food and/or provide specific and desirable functional and technological properties. Pulse byproducts have many nutritional properties, and their technological properties are promising (Comunian et al., 2021).

5.1 | Proteins: Ingredients and foods

Legumes have a high protein content and a good amino acid profile, with the only limiting amino acids being tryptophan and those containing sulfur (Sá et al., 2020). Legume byproducts, such as the seed coat, hull, and husk, contain less protein than the seeds. Indeed, the seed coat has an average protein content of 7.2% (2.30%–15.58%), whereas broken seeds, usually discarded because of imperfections, have an average protein content of ~22.5% (15.76%–29.42%). The average value for pods is 12.5%, whereas for bagasse and chickpea okara, it is ~10%. Soaking and cooking water from legume processing contain only 0.14% and 1.1% protein, respectively. The protein fraction can be increased by extraction, isolation, and concentration to obtain a protein-rich ingredient using the same technologies applied to legume seeds (Kamani et al., 2020; Tassoni et al., 2020). However, food applications incorporating protein ingredients after extraction are limited—typically, the flours/powders of the hulls and pods are incorporated into the formulation without further processing. Because legumes provide an alternative source of proteins, covering all the essential amino acids when combined with cereals (Tassoni et al., 2020), most food applications in the bakery sector involve combinations of legumes and cereals. Snacks, bread, and crackers that have been developed contain on average ~18.3% protein, pasta has ~19.4%, biscuits have ~10%, and meat products have ~14.7%. High-protein beverages and soups (up to 19% and 15% protein, respectively) have also been explored, along with low-protein counterparts (average values of 2.6% and 1.5%, respectively).

5.2 | Dietary fiber: Ingredients and foods

Dietary fiber is one of the most important bioactive components of pulses, particularly beneficial for people living with diabetes, and is used as a functional ingredient in more than 50% of marketed functional foods (Benítez et al., 2011). The European Food Safety Authority and the Food and Agriculture Organization recommend a minimum intake of 25 g/day (Santos et al., 2022). Dietary fiber is a complex and heterogeneous group of substances (cellulose, hemicelluloses, gums, pectins, mucilages, β-glucans, lignins, resistant starch (RS), and non-digestible oligosaccharides, among others) with different physical, chemical, and physiological properties (Macagnan et al., 2016; Singh et al., 2017). They are classed as SDFs (gums, pectins, fructans, inulins, and some hemicelluloses) and IDFs (cellulose, some hemicelluloses, lignins, and arabinoxylan) based on their solubility in water and buffer systems. The optimal ratio in food in terms of health benefits and also technological properties is 30%–50% SDF and 70%–50% IDF (Benítez et al., 2011), although the fiber profile can change after heat treatment (Santos et al., 2022). The seed coat contains an average of 79.82% total dietary fiber (TDF; 3%–9% SDF and 63%–86% IDF), whereas the average value for pods (mainly broad bean and pea) is 44.64% (4%–18% SDF and 31%–86% IDF). The lowest value was found in broken common bean seeds (17.02%). Fiber extracts concentrated to 90% can be prepared as an ingredient for food fortification (Belghith-Fendri et al., 2016b). The functional foods enriched with legume byproducts contain different levels of dietary fibers due to the incorporation of flours/powders with a 2%–30% dietary fiber content, resulting in values of 3.15%–21.7% in the final food product. Bread prepared from chickpea, pea and broad bean byproducts typically contains up to 6.9% dietary fiber, but this increases to a maximum of 18.92% in special high-fiber products. The dietary fiber content of extruded snacks is 6.16%–21.7%, and instant gluten-free pasta prepared from broken seeds can contain up to 19%. Beverages prepared from chickpea hulls contain up to 10% fiber, and high-fiber meat products contain almost 5% fiber. The IDF/SDF ratio ranges from ~2 for noodles and beverages to ~4 for high-fiber bread. This ratio is relevant because the bioactive effect of dietary fiber is also related to polyphenols and other bioactive compounds (Macagnan et al., 2016; Singh et al., 2017). For example, bean and lentil fibers, especially IDF, contain associated hydroxybenzoic and hydroxycinnamic compounds, flavan-3-ols, procyanidins, flavonols, and flavones (Dueñas et al., 2016).

5.3 | Total phenolic content: Ingredients and foods

Legumes are an excellent source of bioactive phytochemicals, including phenolic acids, flavonols, flavones, isoflavones, anthocyanins, tannins, and other phenolics, distributed mainly in the seed coat. Most of the phenolic compounds associated with whole seed are insoluble bound forms, mainly phenolic acids, linked to cell wall components like cellulose, hemicellulose, lignin, and pectin (Nicolás-García et al., 2021). Focusing on the food applications of legume byproducts (Table 2), the flours considered in the food sector contain 56.4–4731 mg gallic acid equivalents (GAE)/100 g flour, reflecting the variability of the starting raw material (seed coat, hull, or husk) due to genetic and agronomic factors that need to be considered for the standardized design of functional foods. The total phenolic content (TPC) of extracts (mostly solid–liquid extracts prepared with water or hydroalcoholic solutions) has been determined to evaluate their use as nutraceuticals, food preservatives, natural antioxidants, encapsulated extracts, and gels. Extracts of pigmented bean seed coat reached TPC values of 4477 mg GAE/100 g comparable to broad bean hull flour (3219–4731 mg GAE/100 g). The chickpea seed coat achieved the highest value of 12,633–13,466 mg GAE/100 g extract, whereas the soaking water of chickpeas, beans, lentils, and peas showed the lowest values ~19 mg GAE/100 g. Enrichment with flours or extracts of legume byproducts could increase the TPC content, and thus the antioxidant activity of functional foods, but few reports have described food applications. Bread containing chickpea husks reached 110 mg GAE/100 g (Niño-Medina et al., 2019) and bread containing common bean seed coats reached 31.28 mg cyanidin-3-glucoside/100 g dry weight (DW; Chávez-Santoscoy et al., 2016). Recently, Chakraborty et al. (2022) developed health drinks from chickpea in which the hulls had a TPC value of ~400 mg GAE/100 g. Pods have been used in pectin and alginate beads as antioxidant ingredients, and the TPC of cowpea pod hydrogels was 22–28 mg/100 mL (Traffano-Schiffo et al., 2020). TPC data for soup, mayonnaise, meat products, and mildly treated snacks would be useful to understand the interactions of the food matrix and to evaluate the shelf life of formulated products.

TABLE 1 Nutritional composition of foods enriched with legume byproducts classified by product category and legume by-product ingredients classified by type of by-product

	PROT	CF	TDF	IDF	SDF	LIP	RS	TC	Reference
BAKERY									
Snack +100% carioca bean, broken	18.5	-	19.7	-	-	14.2	-	64.2	Bento et al. (2021)
Snack + 90% black bean, broken	19.7	-	21.7	-	-	15.4	-	61.1	
Snack + bean, broken	11.27	-	6.16	-	-	0.09	-	78.14	Carvalho et al. (2012)
Snack + bean blend husk/broken	15.1	-	-	-	-	27.38	-	-	U. Tiwari et al. (2011)
Cracker + 5%–15% pea peel	18.93	0.8	-	-	-	-	-	64.61	Mousa et al. (2021)
Biscuit + 5%–25% pigeon pea dehulled	7.28	0.51	-	-	-	19.21	-	67.61	B. K. Tiwari et al. (2011)
Biscuit + 5%–25% pigeon pea byproducts	7.66	0.75	-	-	-	19.51	-	66.65	
Cookies + 15%–30% whole black bean, broken	3.86	-	2.05	-	-	10.19	-	83.73	Bassinello et al. (2011)
Cookies + 15%–30% peeled black bean, broken	3.41	-	1.88	-	-	7.64	-	86.39	
BREAD									
Bread + 2% chickpea fiber	-	-	6.9	2.7	4.2	-	-	-	Niño-Medina et al. (2019)
Bread + 10% pea hulls small-grained	17	-	~15.12	~12.00	~3.12	-	-	-	Kasprzak and Rzedzicki (2010)
Bread + 10% pea hulls coarse-grained	21	-	~18.25	~14.25	~4.00	-	-	-	
Bread + 11%–31% broad bean hull	24.91	-	18.92	-	-	33.72	-	-	Ni et al. (2020)
PASTA									
Gluten free pasta + carioca bean, broken	19.7	-	19.1	-	-	1.15	-	75.9	Bento et al. (2021)
Gluten free pasta + black bean, broken	19.5	-	18	-	-	1.31	-	75.7	
Noodles + 5% chickpea seed coat	9.53	2.54	9.1	6.8	2.3	1.25	-	-	Beniwal and Jood (2015)
Noodles + 20% chickpea, broken	13.1	2.16	8.98	5.03	3.95	2.64	-	-	
SOUP									
Soup + 12.5% pea pod	1.5	-	13.25	-	-	1.9	-	-	Hanan et al. (2020)
Soup + 5%–15% pea peel	14.44	1.07	-	-	-	-	-	64.42	Mousa et al. (2021)
BEVERAGES									
Health drink powder + chickpea hull	19.27	4.95	10.01	7.05	2.96	2.98	-	-	Chakraborty et al. (2022)
Detox tea + chickpea hull	4.47	5.07	10.5	7.21	3.29	3.09	-	-	
Beverage + chickpea CWa	1.5	-	-	-	-	-	0.689	9.01	Lopes et al. (2020)
Beverage + lupin CWa	2.4	-	-	-	-	-	0.006	3.26	
Beverage + lupin + chickpea CWa	2	-	-	-	-	-	0.204	5.36	
MEAT									
Nuggets + 5%–10% chickpea hull	14.35	-	4.99	-	-	9.13	-	-	Arun K. Verma et al. (2012)
Nuggets + 8%–12% pea hull	15.09	-	4.81	-	-	9.13	-	-	Arun K. Verma et al. (2015)

(Continues)

TABLE 1 (Continued)

	PROT	CF	TDF	IDF	SDF	LIP	RS	TC	Reference
SEED COAT									
Broad bean	5	-	82.3	-	-	0.2	0.9	-	Çalışkantürk Karataş et al. (2017)
Broad bean	2.65	-	-	-	-	-	-	-	Renna et al. (2020)
Broad bean	2.3	12.59	-	-	-	-	-	67.23	Barakat et al. (2017)
Broad bean	5.3	-	81.7	-	-	0.4	-	1.1	Ni et al. (2020)
Black bean	12.4	33.72	78.53	69.23	9.3	0.93	-	39.79	Girish et al. (2012)
Chickpea	4.92	28.69	70.37	-	-	0.26	-	80.43	Niño-Medina et al. (2017)
Lupin	8.05	-	81.9	78.93	2.97	2	-	-	Zhong et al. (2020)
Pea (small-grained)	15.58	32.77	70.69	63.26	7.43	-	-	-	Kasprzak and Rzedzicki (2010)
Pea (coarse-grained)	8.05	53.13	93.29	86.67	6.32	-	-	-	
Moth bean	7.96	-	-	-	-	0.65	-	76.43	Kamani et al. (2020)
BROKEN									
Fava bean—proteins	88.45	-	-	-	-	0.57	-	9.04	Abdel-Haleem et al. (2022)
White bean—proteins	79.06	-	-	-	-	0.52	-	18.7	
Cowpea—proteins	83.38	-	-	-	-	0.79	-	13.85	
Common bean	20.2	-	17.02	-	-	0.88	-	64.29	Carvalho et al. (2012)
Bean blend	15.76	-	-	-	-	0.88	-	-	U. Tiwari et al. (2011)
Pigeon pea (de-hulled)	29.42	4.66	-	-	-	5.73	-	54.88	B. K. Tiwari et al. (2011)
Pigeon pea byproducts	24.67	2.79	-	-	-	1.84	-	66.51	
PODS									
Broad bean	13.46	-	53.01	34.69	18.32	0.24	0.2	17.26	Belghith-Fendri et al. (2016a)
Pea	13.37	-	43.88	35.61	8.27	1.06	6.81	24.34	
Broad bean	13.6	-	40.1	30.8	9.3	1.3	11.7	-	Mateos-Aparicio et al. (2010)
Pea	10.8	-	58.6	54.4	4.2	1.3	3.7		
Pea (blanched)	11.99	-	36.12	25.04	11.08	3.88	-	69.5	Hanan et al. (2020) and Rudra et al. (2020)
Pea fibers	6.73	-	89.86	86.38	5.23	0.87	-	-	Belghith- Fendri et al. (2016b)
Broad bean fibers	6.6	-	91.61	85.5	4.36	0.66	-	-	
Pea	35	-	-	-	-	-	-	55.92	Mousa et al. (2021)
SOAKING WATER									
Haricot bean	0.35	-	-	0.99	-	-	-	0.65	Huang et al. (2017)[a]
Chickpea	0.08	-	-	0.25	-	-	-	0.19	
Green lentil	0.08	-	-	0.17	-	-	-	0.04	
Yellow pea	0.60	-	-	0.34	-	-	-	0.69	

(Continues)

TABLE 1 (Continued)

	PROT	CF	TDF	IDF	SDF	LIP	RS	TC	Reference
COOKING WATER									
Haricot bean	0.7	-	-	0.93	-	-	-	0.89	Stantiall et al. (2018)[a]
Chickpea	0.95	-	-	2.37	-	-	-	1.24	
Green lentil	1.51	-	-	2.09	-	-	-	0.61	
Yellow pea	1.27	-	-	1.63	-	-	-	1.72	
OKARA									
Chickpea	9.51	-	-	43.3	-	1.7	-	1.25	Lian et al. (2020)[a]
BAGASSE									
Broad bean	10.21	-	-	-	-	0.06	-	82.11	De La Rosa-MilÍan et al. (2017)
Chickpea	10.43	-	-	-	-	0.03	-	82.07	
Lentil	11.55	-	-	-	-	0.09	-	82.38	
White bean	10.11	-	-	-	-	0.1	-	81.92	

Note: The data, reported as percentages, were adapted to ensure the uniformity of units between the reviewed studies. For food products made with different levels of enrichment, the average value is reported.
Abbreviations: CF, crude fibers; CWa, cooking water; IDF, insoluble dietary fiber; LIP, lipids; PROT, proteins; RS, resistant starch; SDF, soluble dietary fiber; TC, total carbohydrates; TDF, total dietary fiber.
[a]Water-soluble carbohydrates.

TABLE 2 Total phenolic content and antioxidant activity of by-product ingredients and food products

Formulation	TPC mg GAE/100 g DW	DPPH	ABTS mg TE/100 g DW	ORAC	FRAP	Reference
FLOUR						
Fava bean seed coat	2150	2290	-	-	-	Çalışkantürk Karataş et al. (2017)
Fava bean hull	4235	-	-	-	-	Renna et al. (2020)
Chickpea hull	111	-	-	-	115	Johnson et al. (2021)
Chickpea husk	191	-	-	-	130	
Chickpea husk	161[a]	0.002	0.008	-	-	Niño-Medina et al. (2017)
Lupin seed coat	91	37.24	54.20	709.58	-	Zhong et al. (2020)
Bean pod	452	-	0.012	-	-	Martínez-Castaño et al. (2020)
S/L EXTRACT						
Broad bean seed coat	-	73.92[b]	-	-	-	Barakat et al. (2017)
Hull common bean	1127[c]	-	-	2295	-	Oomah et al. (2010)
Bean seed coat	2049	-	0.0012	-	0.0039[j]	Gan et al. (2016)
Mung bean hull	~7100[d]	~4000[g]	-	-	-	Kanatt et al. (2011)
Pigeon pea hull	~13,000[d]	~7000[g]	-	-	-	
Chickpea hull	~7000[d]	~5000[g]	-	-	-	
Chickpea seed coat	13049	3.01[h]	-	-	-	Girish et al. (2012)
Chickpea SWa	2	-	-	-	-	Huang et al. (2017)
Haricot bean SWa	26	-	-	-	-	
Green lentil SWa	42	-	-	-	-	
Yellow pea SWa	5	-	-	-	-	
Pea pod	822	-	-	-	-	Castaldo et al. (2022)
Cowpea pod	37[e]	-	3.03×10^{-9} [e]	-	-	Traffano-Schiffo et al. (2020)
BREAD						
Bread + 2% chickpea fibers	110.2	0.47	1.21		0.50	Niño-Medina et al. (2019)
Bread + 0.5% black bean extract	31.28[f]					Chávez-Santoscoy et al. (2016)
BEVERAGE						
Health drink powder + chickpea hull	401	59.09%				Chakraborty et al. (2022)
Detox tea + chickpea hull	404	57.12%				

(Continues)

TABLE 2 (Continued)

Formulation	TPC mg GAE/100 g DW	DPPH	ABTS mg TE/100 g DW	ORAC	FRAP	Reference
PECTIN/GELS						
Pea pod––encapsulated		5.47×10^{-9}	7.31×10^{-9}		4.91×10^{-9}	Castaldo et al. (2022)
Cowpea pod—hydrogel	25[e]		3.84×10^{-9}[e]			Traffano-Schiffo et al. (2020)
Chickpea husk—pectin		29[i]				Urias-Orona et al. (2010)

Note: The reported data were adapted to ensure the uniformity of units between the reviewed studies. The mean value is reported for formulations with multiple levels of incorporation.

Abbreviations: ABTS, 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); DW, dry weight; DPPH, 2,2-diphenyl-1-picrylhydrazyl; FRAP, ferric antioxidant power; GAE, gallic acid equivalents; ORAC, oxygen radical absorbance capacity; s/l, solid/liquid; SWa, soaking water; TE, Trolox equivalent; TPC, total phenolic content.

[a] mg chlorogenic acid /100 g.
[b] % 200 ppm extract.
[c] mg catechin/100 g extract.
[d] mg catechin/100 g extract.
[e] mg/100 mL.
[f] mg cyanindin-3-glucoside/100 g DW bread.
[g] at the concentration of 50 μg/mL.
[h] IC_{50} μg/GAE.
[i] % at the concentration of 1 mg/mL.
[j] mg Fe (II)/100 g DW.

5.4 | Carotenoids and tocopherols

Carotenoids and tocopherols are lipid-soluble antioxidants and micronutrients. Specifically, they are precursors of vitamin A and isomers of vitamin E (α, β, δ, γ tocopherol and tocotrienol), respectively (Meléndez-Martínez et al., 2021; Peh et al., 2016). In pulses, γ-tocopherol is the most abundant isomer. Murube et al. (2021) detected only the γ and δ isomers across 25 bean accessions. However, the tocopherol content was low in pulse and legume byproducts. Although some tocopherols have been detected in other legume byproducts, such as green lentil hulls (Sun et al., 2020) and pods of cowpea, mung bean, and moth bean (Nehra et al., 2018), the generally low levels have limited the evaluation of such byproducts in functional foods.

Carotenoids are typically more abundant in tissues that contain chlorophyll pigments, including peas and green beans (Schwartz et al., 2008). Pulses are poor sources of carotenoids, compared to leaves, fruits, and vegetables (Girish et al., 2012). The seed coat of black gram had the highest carotenoid content (0.415 mg/100 g), compared to other parts of the legume, as seen in the whole gram, cotyledon, germ, aleurone layer, and plumule fractions. These compounds are mainly present in the seed coat of pulses, which is generally removed during milling, but represent 25% of the black gram (Girish et al., 2012). Green pea pods were found to be a good source of carotenoids and chlorophyll, which could be incorporated as functional ingredients in food products (Belghith-Fendri et al., 2016a; Hanan et al., 2020; Rudra et al., 2020). The carotenoid and chlorophyll content of instant soup powder increased following the addition of 12.5% pea pod powder, from 4.47 to 6.65 mg/100 g carotenoids and from 1.12 to 1.95 mg/100 g chlorophyll (Hanan et al., 2020). Furthermore, different types of carotenoids and chlorophylls accumulate at various points during the development of pea hulls. The prominent ones observed at all stages (including maturity) were chlorophylls *a* and *b* and the xanthophyll lutein, whereas violaxanthin and β-carotene also accumulated in immature hulls but had fallen to trace amounts by maturity (Marles et al., 2013). Alternatively, legume byproducts can be used as substrates for the production of carotenoids by suitable microorganisms. For example, mung bean husks, pea pods, and other agro-industrial waste were used as substrates by *R. mucilaginosa* (R. Sharma & Ghoshal, 2020), and mesquite pods were used as a substrate by *Xanthophyllomyces dendrorhous* (Villegas-Méndez et al., 2019), in each case for carotenoid biosynthesis. In addition to their health-promoting properties, carotenoids and chlorophylls (along with other phenols) play a key role in the color of a food product, and thus its acceptability, suggesting legume byproducts could be developed as food colorings (Sant'Anna et al., 2013).

5.5 | Antinutrients

Although there is a debate around whether antinutritional factors should be eliminated or retained, Escobedo and Mojica (2021) concluded that pulse-based snack production should focus mainly on reducing the amount of α-galacto-oligosaccharides because they cause digestive discomfort, and thus reduce consumer acceptance. After processing, the effects of antinutritional factors such as tannins, phytic acid, saponins, and trypsin inhibitors may not be significant. Several factors can influence the abundance of antinutrients, such as climatic conditions, location, and variety. Genetic improvement can be used to develop varieties that contain less phytic acid (Campos-Vega et al., 2010; Escobedo & Mojica, 2021). Several methods can be used to eliminate or modify antinutrients as discussed below.

5.5.1 | Phytic acid

Phytic acid is the main antinutrient in legumes (Castaldo et al., 2022; Ojo, 2021). As a strong chelating agent, it can form complexes with proteins and minerals (e.g., Ca, Fe, Zn, and Mg), and thus makes such nutrients unavailable, leading to micronutrient deficiencies (Y. Kumar et al., 2021; Ojo, 2021). However, a low level of phytic acid has antioxidant and antidiabetic and antibacterial activity while also lowering cholesterol and triglyceride levels in the blood, inhibiting kidney stone formation, and possibly protecting against cancer (Y. Kumar et al., 2021). Phytic acid is predominately located in the cotyledons and protein bodies of the seed, whereas lower quantities are present in seed coats and pods (Campos-Vega et al., 2010). Accordingly, broken seed contains more phytic acid than hulls, husks, and pods, and dehulling increases its concentration. In aqueous extracts of pea pods, the phytic acid concentration ranged from 51.6 to 65.3 mg/100 g (Castaldo et al., 2022). The phytic acid content of pulse hulls (lentil, broad bean, and pea) was almost 25% of the whole seed, ranging from 137 to 166 mg/100 g (Kaya et al., 2018). For chickpea, the seed coat contained 12 times less phytic acid than cotyledon, 79 versus 982 mg/100 g DW, but the addition of chickpea husks increased the phytic acid level to 200 mg/100 g in a heath drink powder and detox tea substitute (Chakraborty et al., 2022). The authors concluded that the phytic acid levels were negligible, compared with chickpea seeds. Washing, cooking, fermentation, and processing of the husk also decreased the level of phytic acid (Chakraborty et al., 2022).

5.5.2 | Trypsin inhibitors

Trypsin inhibitors reduce the digestion and absorption of dietary proteins and are mainly present in seed cotyledons (Avilés-Gaxiola et al., 2018). In pods, the level of such compounds declines with maturation to far below the level detected in seeds, suggesting that little or no processing would be required (Alizadeh et al., 2012). When chickpea husks were incorporated into beverages, the trypsin inhibitor (TI) content was 2 TI units/mg in a healthy drink powder and ~3 TI units/mg in a detox tea substitute, which falls within the healthy range for antinutrients in the body (Chakraborty et al., 2022). The method most widely used to inactivate trypsin inhibitors is thermal treatment (e.g., 15 min at 100°C). The pressure cooking and boiling of cowpea pods were found to reduce the trypsin inhibitor content (Deol & Bains, 2010). Extrusion was the best method to abolish trypsin inhibitor activity without modifying the protein content of fava and kidney beans (Alonso et al., 2000).

5.5.3 | Tannins

Tannins are bitter polyphenolic compounds that bind proteins and other organic molecules (such as alkaloids and amino acids), causing them to precipitate. In legumes, the presence of tannins makes the protein unavailable and decreases protein digestibility (Abbas & Ahmad, 2018). Condensed non-hydrolyzed tannins are important compounds produced in the seed coat that confer color. The condensed tannin content of fava bean seed coats is substantially higher than other legume seeds due to the greater thickness of the seed tegument. The total condensed tannin content was found to be 47.7 mg catechin equivalents (CE)/g in fava bean seed coat flour, much higher than the 1.9 mg CE/g in whole fava bean flour (Çalışkantürk Karataş et al., 2017). In raw wild bean pods, the tannin level of 2.8 mg/g decreases to 1.9 mg/g when cooked (B. B. Sharma et al., 2006). Tannins are thermolabile and can therefore be eliminated by high-temperature treatment. Both pressure cooking and boiling of cowpea pods reduced the tannin levels as a function of processing time (Deol & Bains, 2010).

5.5.4 | Alkaloids

Quinolizidine alkaloids are abundant in legume plants but are traditionally considered undesirable because they act as antinutrients. However, recent studies have shown that certain alkaloids benefit human health when included in the diet (Ku et al., 2020). The total alkaloid content varies among legume species, for example, from 0.02% to 12.73% of dry seed weight in lupins (Kroc et al., 2017). However, the total safe amount of alkaloids is limited to 0.02% of the seed's DW (Frick et al., 2017).

5.5.5 | Saponins

Saponins are antinutrients that limit the absorption of protein, sugar, and cholesterol (Serventi, 2020). Black bean seed coats incorporated into whole wheat bread retained more than 90% of their saponin content after baking (Chávez-Santoscoy et al., 2016). However, germination and soaking are strategies to reduce saponin levels, and in the case of black beans, this reduced the saponin content of the seed coat to below that of the sprouts and cotyledons (Guajardo-Flores et al., 2012). During the soaking, washing, and blanching of seed coats, some saponins are dissolved in the water and are lost (Shi et al., 2004). As consequence, the soaking water of beans, peas, and lentils, provides saponins when incorporated into functional foods such as gluten-free bread. Different factors could be responsible for the level of saponin present in soaking water, such as soaking time, hull thickness, and the size and shape of legume seeds (Huang et al., 2017).

5.5.6 | Fermentable oligo/di/monosaccharides and polyols (FODMAPs)

FODMAPs are components of several plant-based foods, including fruits, vegetables, and pulses (Nyyssölä et al., 2020). In addition, α-galacto-oligosaccharides such as raffinose, verbascose, and stachyose are present in most pulses (Escobedo et al., 2021). These saccharides are poorly absorbed in the small intestine and are fermented in the colon by gut bacteria, producing short-chain fatty acids and gas, leading to uncomfortable effects such as diarrhea and meteorism (Suárez-Martínez et al., 2016; Takagi et al., 2016). The carbohydrates are located mainly in the seed cotyledon and are thought to store energy for plant development (Blöchl et al., 2007). Therefore, seed dehulling would not reduce the concentration of FODMAP components (Moussou et al., 2017). Enzymatic treatment, fermentation, and seed germination are the most effective techniques to reduce the concentration of saccharides in the final product and increase consumer acceptance (Escobedo et al., 2021).

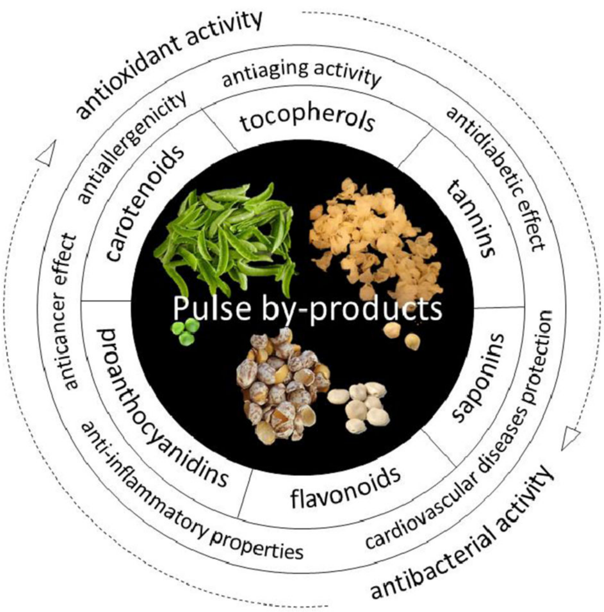

FIGURE 2 Composition of bioactive compounds present in the reviewed legume byproducts and corresponding health benefits. Bioactive compounds derived from the extracts of legume byproducts can be described as hydrophilic (proanthocyanidins, flavonoids, saponins, tannins) and lipophilic (carotenoids and tocopherols). Bioactive compounds represented in the legume byproducts exhibit health-promoting antioxidant and antibacterial activities.

6 | HEALTH PROPERTIES

Previous studies reported that pulse byproducts contain high levels of bioactive compounds (Dueñas et al., 2006; Kanatt et al., 2011; Sun et al., 2020) such as phenolics, carotenoids, tocopherols/tocotrienols, and others (Figure 2). All these fractions help to neutralize free radicals, hence acting as antioxidants (Dueñas et al., 2006; Kanatt et al., 2011; Sun et al., 2020). Free radicals generated from oxygen, nitrogen, and sulfur during cellular metabolism react with other molecules via their unpaired electrons and play a key role in cell signaling, apoptosis, and gene expression. Nevertheless, high levels of free radicals can attack amino acid side chains in proteins, nucleic acid bases, and double bonds in fatty acids, causing oxidative stress that increases the risk of cardiovascular and neurodegenerative diseases, cancer, autism, atherosclerosis, and diabetes (Lü et al., 2010). Moreover, oxidation reactions are a major concern in the food industry, and antioxidants are widely used to prevent them. Although the seed coat represents a small part (10%–11%) of the total seed weight of grain legumes, it contributes most of the antioxidant activity (Kanatt et al., 2011). This is because the TPC of legume hulls is three to eight times higher than that of the seed (Dueñas et al., 2006; Oomah et al., 2011). Hulls also contain more diverse phenolic compounds than cotyledons. For example, only low concentrations of hydroxybenzoic and hydroxycinnamic acid were found in lentil cotyledons, whereas 43 phenolic compounds were identified in the seed coat (Dueñas et al., 2002; Mirali et al., 2017). Polyphenols are the major plant compounds with proven in vitro antioxidant activity, also conferring anti-inflammatory and antiproliferative effects against cancer cells (Zhang et al., 2015; Zhao et al., 2014). Among other common legume byproducts, lentil seed coats showed the highest level of polyphenolic (flavonoid) compounds (47.6 mg/g), and therefore the greatest antioxidant activity measured by different in vitro assays (Table 2) such as the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging and β-carotene bleaching assays (Zhao et al., 2014). Pigeon pea seed coat contained a lower level of phenolic compounds than lentils, but a higher level than chickpea, common bean, and mung bean (Kanatt et al., 2011). The lack of an accurate assessment of the TPC may lead to an underestimation of the potential health benefits of these compounds. Pigeon pea hull extract also showed antibacterial activity against *Bacillus cereus*, which causes foodborne illnesses.

Carotenoids and tocopherols (especially γ-tocopherol) are the major lipophilic antioxidants in lentils, with a higher content in hulls than in whole seeds. Lutein and zeaxanthin are strong antioxidants that can protect human cells from carcinogens, and they are also necessary for eye health (Raman et al., 2019). Tocopherols and tocotrienols act as strong antioxidants, protecting oils from oxidation (Sun et al., 2020). Due to the low concentration of lipophilic antioxidants in pulses, only a few studies have considered their contribution to the overall antioxidant activity of such products (P. X. Chen et al., 2015; Zhang et al., 2015). Common bean pods contain polyphenols (e.g., rutin and saponins) with antioxidant activity in vitro and act against uropathogenic *Escherichia coli* (Popowski et al., 2021). Extractable polyphenolics from broad bean and pea pods possess high in vitro antioxidant capacity (Mateos-Aparicio et al., 2012). There is growing scientific interest in the properties of polyphenols in the prevention of age-related diseases such as cancer and cardiovascular disease. Moreover, the high dietary fiber content of broad bean and pea pods confers prebiotic activity, which is a significant factor in the prevention of cardiovascular disease (Mateos-Aparicio et al., 2012). Furthermore, pectin extracted from chickpea husks was highly active in the DPPH radical scavenging assay and should be explored as a novel antioxidant (Urias-Orona et al., 2010).

The comprehensive profiling of compounds with antioxidant activity lays a good foundation for the value-added uses of legume hulls/husks and pods. The next challenge is the development of functional foods enriched with these byproducts, validated and tested for their palatability, health, and efficacy in reducing the risk of diseases through in vivo studies.

7 | TECHNO-FUNCTIONAL PROPERTIES OF INGREDIENTS

The technical and functional properties of food products reflect their essential physicochemical properties based on interactions between structures and molecules in different compositions of ingredients. Therefore, evaluating the functional characteristics of ingredients may help to predict their behavior in specific food systems and thus the quality of the food (Godswill et al., 2019). As summarized in Table 3, the most interesting properties of food processing include solubility, emulsification, foaming, gelation, and the ability to bind water and fat (Boye et al., 2010).

7.1 | Solubility

The solubility of proteins is an important prerequisite in food systems where they act as a functional ingredient (Amagliani & Schmitt, 2017). For example, high solubility is typically required for the development of liquid products, whereas this could be detrimental in solid products because it might hinder proper texturization. Generally, plant proteins are characterized by poor solubility in water, falling to a minimum between pH 4 and 6. By shifting the pH toward more acid or alkaline conditions, solubility increases due to the higher degree of electrostatic repulsion between protein molecules (Amagliani & Schmitt, 2017; Boye et al., 2010). These findings were confirmed by Abdel-Haleem et al. (2022), who evaluated the solubility of the protein isolates obtained from broken fava bean, white bean, and cowpea used for the development of vegan mayonnaise.

7.2 | Emulsifying properties

Emulsifying properties are often determined by measuring the emulsifying activity (EA) or EA index (EAI) and the emulsifying stability (ES) or ES index (ESI) (Boye et al., 2010; Grasso et al., 2022). The EA is expressed as a percentage of the height of the emulsified layer divided by the height of the entire layer in the tube, and the EAI (expressed in m^2/g) considers the absorbance of the emulsion, the dilution factor, the density of the sample, and the volume of the oil fraction. Similarly, the ES is calculated as a percentage of the height of the remaining emulsified layer divided by the height of the whole layer in the tube after a certain time, and ESI (expressed in min) considers the difference in absorbance at time 0 and the end.

Emulsifying properties generally depend on the oil/water ratio, food components, droplet size, and ratio of hydrophilic/hydrophobic amino acids and the configuration and concentration of proteins (Syed et al., 2022). Indeed, the amphiphilic nature of proteins makes them excellent natural emulsifiers by absorbing at the interface of water/oil emulsions and stabilizing dispersions (Kim et al., 2020; Syed et al., 2022; Tang & Huang, 2022). Among the various ingredients investigated, those with the highest protein concentrations (broken broad bean, white bean, and cowpea seeds: 79.06%–88.45% protein) showed the best emulsifying properties, with broad bean achieving the highest EAI (69.16 m^2/g) and ESI (95.27 min), albeit with differences between varieties (Abdel-Haleem et al., 2022). Similarly, Belghith-Fendri et al. (2016a) and Huang et al. (2017) found the same differences among varieties when assessing pea byproducts, finding that pod and soaking water, respectively, had the highest EAs. Given that the protein concentration of pea soaking water (0.6%) reported by Huang et al. (2017) was higher than the others, the good EA may be attributed not only to the protein concentration and composition but also to the presence of other components such as water-soluble carbohydrates and saponins, which can act as surfactants. The ES of moth bean seed coats reported by Kamani et al. (2020) was ~7-fold lower than chickpea cooking waters reported by Mustafa et al. (2018) and Shim et al. (2021), and this was attributed to the high carbohydrate content (mainly fibers) with poor stability.

7.3 | Foaming properties

Foaming capacity (FC) and foaming stability (FS) are indices used to evaluate foaming properties, which are important in the development of beverages, mousses, and whipped toppings. FC is usually expressed as a percentage of the volume increase after high-speed whipping, whereas FS indicates the change in the volume of foam over a certain period (usually 30 min), even though different methods may be applied for such measurements (Boye et al., 2010). FC and FS vary greatly among varieties and types of byproducts. Cooking waters displayed the best foaming properties, especially chickpea cooking water (FC = 227%–331% and FS = 84.41%–76.5%), making it particularly interesting as a potential egg white replacement. It is noteworthy that the excellent foaming properties of cooking waters may be related to the protein composition or rather to the presence of albumins (Stantiall et al., 2018). Although albumins are a minor storage protein component in legume seeds (10%–30% of total protein), compared

TABLE 3 Techno-functional properties of legume ingredients classified by type of by-product

Legume	EAI m^2/g	ESI min	FC %	FS %	LGC %	WAC g/g	WSI %	SC mL/g	OAC g/g	V_{fin} Pas	Reference
SEED COAT											
Pea	-	-	-	-	-	5.55	-	3.95	1.75	-	Zhong et al. (2018)
Chickpea	-	-	-	-	-	6.20	-	3.60	1.80	-	
Mung bean	-	-	-	-	-	3.79	-	7.36	1.66	-	
Lentil	-	-	-	-	-	3.60	-	2.40	1.60	-	
Moth bean	55%[a]	11%[b]	13.8	7.33	16	3.77	7.95	-	1.36	-	Kamani et al. (2020)
BROKEN											
Cowpea protein	58.4	92.7	35.3	50.0	-	1.50	-	-	1.14	-	Abdel-Haleem et al. (2022)
Fava bean protein	69.2	95.3	40.0	43.6	-	2.50	-	-	1.42	-	
White bean protein	49.1	71.1	28.3	60.5	-	2.00	-	-	1.26	-	
Carioca bean (macerated)	-	-	-	-	-	3.98	4.34	-	1.92	1.14	Bento et al. (2021)
Carioca bean	-	-	-	-	-	3.40	5.58	-	2.00	4.18	
Black bean (macerated)	-	-	-	-	-	3.65	4.97	-	1.90	1.53	
Black bean	-	-	-	-	-	3.57	5.40	-	2.04	7.14	
PODS											
Pea fibers	-	-	-	-	-	4.64	-	-	2.86	-	Belghith-Fendri et al. (2016b)
Broad bean fibers	-	-	-	-	-	6.98	-	-	3.39	-	
Pea	14.5	52.4	23.0	-	12	3.69	-	5.00	1.14	-	Belghith-Fendri et al. (2016a)
Broad bean	8.8	56.6	10.0	-	10	4.46	-	4.98	1.42	-	
Pea	-	-	-	-	-	16.1	-	-	13.4	-	Rudra et al. (2020)
Bean (convection drying)	-	-	-	-	-	8.30	-	-	2.53	-	Martínez-Castaño et al. (2020)
Bean (vacuum drying)	-	-	-	-	-	7.56	-	-	2.56	-	
SOAKING WATER											
Yellow peas	50%[a]	-	-	-	-	-	-	-	-	2.53	Huang et al. (2017)
Chickpeas	46%[a]	-	-	-	-	-	-	-	-	2.56	
Haricot beans	37%[a]	-	-	-	-	-	-	-	-	2.47	
Green lentils	18%[a]	-	-	-	-	-	-	-	-	2.47	
COOKING WATER											
Chickpea	-	69%[b]	331	84.41	-	-	-	-	-	-	Mustafa et al. (2018)
Chickpea	1.10	76%[b]	227	76.5	-	-	-	-	-	-	Shim et al.,(2021)
Chickpea	-	-	58	-	-	-	-	-	-	0.05[c]	Stantiall et al. (2018)
Haricot bean	-	-	39	-	-	-	-	-	-	0.01[c]	
Green lentil	-	-	97	-	-	-	-	-	-	0.03[c]	

(Continues)

TABLE 3 (Continued)

Legume	EAI m^2/g	ESI min	FC %	FS %	LGC %	WAC g/g	WSI %	SC mL/g	OAC g/g	V_{fin} Pas	Reference
Yellow pea	-	-	93	-	-	-	-	-	-	0.01[c]	
OKARA											
Chickpea	4.15	-	-	-	-	6.01	-	-	2.38	-	Lian et al. (2020)
BAGASSE											
Chickpea	-	-	-	-	-	2.78	7.25	4.45	3.78	1.15	De La Rosa-MilÍan et al. (2017)
White bean	-	-	-	-	-	2.33	7.02	4.37	3.85	1.00	
Broad bean	-	-	-	-	-	2.89	7.16	4.06	3.49	0.50	
Lentil	-	-	-	-	-	2.65	7.14	3.86	3.65	0.65	

Note: The data were adapted to ensure the uniformity of units between the reviewed studies.

Abbreviations: EAI, emulsifying activity index; ESI, emulsifying stability index; FC, foaming capacity; FS, foaming stability; LGC, least gelation concentration; WAC, water absorption capacity; WSI, water solubility index; SC, swelling capacity; OAC, oil-absorption capacity; V_{fin}, final viscosity.

[a]% emulsifying activity (EA).

[b]% emulsifying stability (ES).

[c]Not measured by means Rapid Visco Analyzer.

to globulins (50%–90%), the albumins are soluble in water, whereas globulins require a high concentration of salt. The glutelins (0%–25%) can be extracted in alkali/acid solutions, and the prolamins (0%–7%) require extraction in alcohol (Day, 2013; Grasso et al., 2022; Loveday, 2019).

7.4 | Gelling properties

The gelling capacity is often determined by measuring the least gelling concentration (LGC), namely, the lowest concentration of the ingredient required to obtain a gel: the lower the LGC, the higher the gelling capacity. This property is particularly important in food applications such as jellies or desserts (Boye et al., 2010). Although few authors have determined the LGC of their ingredients (Belghith-Fendri et al., 2016a; Kamani et al., 2020), they obtained similar values ranging from ∼11% (10%–12%, broad bean and pea pods) to ∼16% (moth bean seed coats). The higher gelling capacity of pods, compared to seed coats, may reflect the higher concentration of proteins (13.37%–13.46% vs. 7.96%) and soluble fibers (18% for broad bean, 8% for pea pods, and not specified for moth bean seed coat).

7.5 | Hydration and oil-absorption capacity (OAC)

WAC, water solubility index (WSI), and swelling capacity (SC) are parameters usually applied to measure the hydration capacity of ingredients. WAC indicates the amount of water absorbed per gram of product, WSI determines the weight of dry solids released in the supernatant from the WAC test expressed as a percentage of the original weight of the sample, and SC is the volume in milliliters taken up by the swelling of 1 g of food material (Yousf et al., 2017).

WAC is an important parameter for food processing applications. Ingredients with a low WAC may not be able to hold water effectively, while those with a high WAC may render food products brittle and dry, especially during storage (Boye et al., 2010). Bagasse showed the lowest WAC (2.7 g/g on average), followed by broken seeds at 2.9 g/g, seed coats at 4.6 g/g, and pods at 7.4 g/g. High WACs may be attributed to the presence of hydrophilic components (e.g., carbohydrates, proteins, and dietary fibers) but may also reflect the particle size, 0.5 mm being optimal (Godswill et al., 2019; Santos et al., 2022).

Most studies reported WSI values of ∼7%. Only Bento et al. (2021) described lower values (4.34%–5.58%) for carioca and broken black beans, pointing out that maceration (6 h of soaking plus cooking for 15 min at 121°C) negatively affects this parameter. SC values ranged from 2.4 to 7.36 mL/g for lentil and mung bean seed coats, respectively (Zhong et al., 2018). The SC value of starch depends on the particle size as well as the WAC and also on the amount and proportion of amylose/amylopectin that varies according to the plant source (Godswill et al., 2019; Santos et al., 2022).

Similar to WAC, OAC is expressed as the amount of oil absorbed per gram of product, and it depends mainly on protein conformation, amino acid composition, and surface hydrophobicity. The ability of an ingredient to absorb oil can influence organoleptic and textural properties, enhancing the flavor and mouthfeel of the final product (Godswill et al., 2019; Grasso et al., 2022). In all the studies considered herein, the OAC was lower than 3.9 g/g, except for pea pod powder (13.38 g/g) analyzed by Rudra et al. (2020), which makes this ingredient suitable for high-fat preparations such as mayonnaise.

7.6 | Viscosity

Viscosity is one of the main functional properties of starch and starch-based materials. It can be measured using a Rapid Visco Analyzer (RVA), namely, a heating and cooling viscometer that provides the viscosity profile of a slurry (flour + water) subjected to stirring and heat (Balet et al., 2019). During the heating step, viscosity increases due to starch gelatinization (rupture of intramolecular bonds), and this provides information on the baking performance in terms of structure and mouthfeel of the product. Moreover, the viscosity rises again after the cooling step, indicating starch retrogradation (because starch tends to recover the structure of origin).

In Table 3, final viscosity values were recorded because this indicates the ability of a n ingredient to form a viscous paste after cooking and cooling. Among all RVA studies, Bento et al. (2021) obtained the highest viscosity values for broken black and carioca beans (7.14 and 4.18 Pas, respectively). These values were higher than the macerated beans, suggesting that maceration causes the collapse of starch granules. Huang et al. (2017) and De La Rosa-Millán et al. (2017) reported lower viscosities for soaking waters (∼2.5 Pas) and bagasse (∼0.8 Pas) obtained from different varieties of beans, lentils, peas, and chickpeas without detecting any significant differences among them.

To summarize, the functional properties of ingredients may be influenced by different factors (e.g., composition, conformation, particle size, processing), and their evaluation is important for the development of new foods.

8 | TECHNO-FUNCTIONAL PROPERTIES OF FOOD

The techno-functional properties of food, such as color and texture (Table 4), are used by consumers to assess food quality, playing an important role in whether consumers accept the product or not (Foegeding et al., 2011; Sant'Anna et al., 2013). Color is usually expressed in terms of CIE (Commission Internationale de l'Elcairage) coordinates, namely, L*, a*, and b*. L* indicates the brightness (0 = black; 100 = white), a* the degree of redness (positive values) or greenness (negative values), and b* the degree of yellowness (positive) and blueness (negative). Among foods enriched with legume byproducts, the L* value was generally higher than 70 with few exceptions, whereas a* varied from –12 for bread containing haricot bean soaking water to 9.27 for cakes containing broad bean pods, therefore appearing mostly grayish. The greatest variation was observed for b*, ranging from –2.8 to 65.44 for bread containing yellow pea soaking water and cakes containing pea pods. Color parameters depend on the type and content of natural pigments (e.g., carotenoids, chlorophylls, and phenolics) present in the final food (Sant'Anna et al., 2013), as well as the food processing method, because these compounds are susceptible to heat, air, and pH, which may degrade or transform them (Sant'Anna et al., 2013).

In terms of rheological properties, most authors determined the textural properties of food products by texture profile analysis (TPA) using a texture analyzer, although with little variation (e.g., load cell, probe, compression procedure). TPA (or "two bite test") mimics the mouth's binding action by performing two compression cycles, and different attributes (e.g., hardness and adhesiveness) can be evaluated. Hardness is an important parameter for new foods because it can affect oral processing, such as the amount of chewing required (Campbell et al., 2017). Meat products, especially chickpea hull-enriched nuggets, displayed the highest hardness values (86.43–115.13 N), which reflects the maximum force required during the first compression cycle (Trinh & Glasgow, 2012). Interestingly, bread and bakery products made with chickpea cooking/soaking water displayed the lowest hardness values (23.73 and 3.11 N, respectively), whereas the value was higher when haricot beans were used instead (41.15 and 18.57 N). Stantiall et al. (2018) found a significant inverse correlation between hardness and IDF in meringues, but this was not observed in bread. Therefore, the ingredient composition, food processing operations (e.g., fermentation and extrusion), and processing conditions (e.g., temperature and pressure) affect food structure/texture, including hardness.

Springiness is the rate at which the deformed product returns to its original shape/size (Trinh & Glasgow, 2012), but this cannot always be determined because some foods are destroyed after the first compression as is the case for meringues. Low springiness values (< 1 mm) were observed when foods were prepared with soaking water, whereas the highest values were observed for products containing pods and seed coats. The latter byproducts also have higher protein and fiber contents (Table 1), so this finding agrees with Javanmardi et al. (2021), who stated that springiness is directly proportional to protein and fiber content.

Adhesiveness, defined as the work necessary to pull a compressing probe away from food (Trinh & Glasgow, 2012), is the most important property for semi-solid food such as mayonnaise. Clear differences were detected for mayonnaises enriched with broken pulses, ranging from –10.56 N for fava bean to –5.04 N for cowpea. Park et al. (2020) stated that, among semi-solid foods with similar viscosities, higher adhesiveness makes food harder to swallow. Because mayonnaise products containing broken fava bean and cowpea have the same viscosity (10 Pas), the latter would be more difficult to swallow.

Cohesiveness indicates how well the product withstands a second deformation relative to its resistance under the first deformation. Within each product category, no significant differences were highlighted, except for vegan mayonnaise containing fava bean, which showed a value more than double that of other mayonnaises (1.5 vs 0.6). Chewiness applies only to solid products and is calculated as hardness × cohesiveness × springiness. Meat products displayed very high values (> 343 Nmm), whereas the chewiness of bread ranged from 0.22 to 53.93 Nmm, with bread containing 11%–31% broad bean hulls having the highest value. This agrees with Javanmardi et al. (2021), who showed that increasing the fiber and protein content and WAC also increase the chewiness.

In conclusion, legume byproducts can be incorporated into several foods and the evaluation/improvement of the techno-functional properties of foods enriched with them is essential to ensure consumer acceptance because consumers use these parameters as a measure of quality.

9 | SENSORY PROPERTIES

Consumer acceptance plays a key role in the evaluation of newly developed functional food products (Świąder & Marczewska, 2021). Regardless of a product's health benefits, it will be not successful without consumer acceptance, which is based on the flavor, taste, texture, and appearance, including color (Lawless & Heymann, 2010). The acceptance rate is determined by trained and

TABLE 4 Techno-functional properties of foods made with legume byproducts, classified by product category

Food application	Color L*	a*	b*	Hardness N	Springiness mm	Adhesiveness N	Cohesiveness -	Chewiness Nmm	Reference
BAKERY									
Cake + 5%–30% pea pod	53.0	3.6	65.4	4.86	19.8	1.29	0.27[f]	-	Belghith-Fendri et al. (2016a)
Cake + 5%–30% broad bean pod	27.6	9.3	29.9	7.23	22.6	1.97	0.27[f]	-	
Cake + chickpea CWa	82.1[c]	5.8[c]	20.9[c]	14.2[c]	54.2[c,g]	-	0.53[c]	34.3[g]	Mustafa et al. (2018)
Meringue + yellow pea CWa	97.7	−2.1	5.8	10.8	-	-	-	-	Stantiall et al. (2018)
Meringue + chickpea CWa	97.9	−7.0	16.5	3.11	-	-	-	-	
Meringue + haricot bean CW	93.7	−0.4	5.9	18.6	-	-	-	-	
Meringue + lentil CWa	97.9	−7.2	13.6	4.83	-	-	-	-	
Cookies + 15%–30% peeled black bean, broken	75.57	-	-	12.6	-	-	-	-	Bassinello et al. (2011)
Cookies + 15%–30% whole black bean, broken	74.21	-	-	19.8	-	-	-	-	
BREAD									
Bread + 0.25%–1% pea pod	76.4[c]	−0.3[c]	21.4[c]	8.95	9.56	2.13	0.28[f]	23.0	(Belghith- Fendri et al., 2016b)
Bread + 0.25%–1% broad bean pod	71.4[c]	−0.1[c]	17[c]	10	9.23	2.42	0.26[f]	23.0	
Bread + yellow pea SWa	103	1.9	−2.8	27.6	0.91	0.05[b]	0.28	7.04[d]	(Huang et al., 2017)
Bread + chickpeas SWa	98	−0.4	1.8	23.7	0.68	0.08[b]	0.28	4.52[d]	
Bread + haricot beans SWa	96	−12	29	41.2	0.94	0.10[b]	0.24	9.28[d]	
Bread + green lentils SWa	87	−5.2	15	39.3	0.92	0.19[b]	0.33	11.9[d]	
Bread + 2% chickpea okara	75.6	−0.97	10.1	41.3	-	-	-	-	Lian et al. (2020)
Bread + 0.5% black bean extract	52.4[c]	2.81[c]	10.6[c]	2.65	-	-	0.85	0.22	Chávez-Santoscoy et al. (2016)
Bread + 11%–31% broad bean hull	43.5	-	-	24.1	6.38	0.001[b]	0.35	53.9[d]	Ni et al. (2020)
Bread + 0.15%–2% chickpea fibers	70.0[a]	8.90[a]	27.6[a]	69.7[e]	-	-	-	-	Niño-Medina et al. (2019)
PASTA	-	-	-	-	-	-	-	-	
SOUP	-	-	-	-	-	-	-	-	
BEVERAGES	-	-	-	-	-	-	-	-	
MEAT									
Nuggets + 5%–10% chickpea hull	-	2.44	2.68	115	8.10	0.02	0.42	391[d]	Arun K. Verma et al. (2012)
Nuggets + 8%–12% pea hull	-	2.68	3.03	86.4	8.27	−0.04	0.48	343[d]	Arun K. Verma et al. (2015)

(Continues)

TABLE 4 (Continued)

Food application	Color L*	a*	b*	Hardness N	Springiness mm	Adhesiveness N	Cohesiveness -	Chewiness Nmm	Reference
OTHER									
Mayonnaise + 5%–10% pea pod	-	-	-	0.24	-	0.11	-	-	Rudra et al. (2020)
Mayonnaise + white bean	-	-	-	0.15	-	–7.66	0.67	-	Abdel-Haleem et al. (2022)
Mayonnaise + fava bean	-	-	-	0.15	-	–10.6	1.49	-	
Mayonnaise + cowpea	-	-	-	0.25	-	–5.04	0.63	-	

Note: The data were adapted to ensure the uniformity of units between the reviewed studies. For food with different enrichment levels, the mean value was reported.
Abbreviations: CWa, cooking water; SWa, soaking water.
[a]Referred to crust (mean value Day 0–3).
[b]Expressed as joules.
[c]Referred to the crumb.
[d]Calculated as hardness × springiness × cohesiveness.
[e]Not measured with a texture analyzer.
[f]Expressed as mm.
[g]Expressed as %.

TABLE 5 Sensory evaluation of foods enriched with legume byproducts classified by food category

Food application	No of judges	Trained judges	Type of scale	OA	Reference
BREAD					
Bread + 0.5% black bean extract	40	No[a]	5	4.07	Chávez-Santoscoy et al. (2016)
Bread +0.25%–1% pea pod fibers	40	No	5	3.39	Belghith-Fendri et al. (2016b)
Bread + 0.25%–1% broad bean pod fibers	40	No	5	3.27	
BAKERY					
Snack +100% carioca bean broken	120	No	9	6.8	Bento et al. (2021)
Snack + 90% black bean broken	120	No	9	5.7	
Snack + bean broken	100	No	9	6.83	Carvalho et al. (2012)
Snack + bean blend husk/broken	15	No	9	6.79	U. Tiwari et al. (2011)
Cracker + 5%–15% pea peel	10	No	9	8.4	Mousa et al. (2021)
Cookies + 15%–30% whole black bean, broken	104	No	9	6.21	Bassinello et al. (2011)
Cookies + 15%–30% peeled black bean, broken	104	No	9	5.74	
Cake + 5%–30% pea pod	40	No	5	3.14	Belghith-Fendri et al. (2016a)
Cake + 5%–30% broad bean pod	40	No	5	3.07	
Meringue + haricot bean CW	40	No	9	6.3	Stantiall et al. (2018)
Meringue + chickpea CWa	40	No	9	6.1	
Meringue + lentil CW	40	No	9	5.6	
Meringue + yellow pea CWa	40	No	9	6.3	
PASTA					
Gluten free pasta + carioca bean, broken	120	No	9	6.4	Bento et al. (2021)
Gluten free pasta + black bean, broken	120	No	9	6.5	
SOUP					
Soup + 10%–20% pea pod	10	No	9	7	Hanan et al. (2020)
Soup + 5%–15% pea peel	10	No	9	8.7	Mousa et al. (2021)
BEVERAGES	-	-	-	-	
MEAT					
Nuggets + 5%–10% chickpea hull	10	Yes	8	6.59	Arun K. Verma et al. (2012)
Nuggets + 8%–12% pea hull	10	Yes	8	6.9	Arun K. Verma et al. (2015)
OTHERS					
Mayonnaise + 5%–10% pea pod	20	No	9	8.25	Rudra et al. (2020)
Mayonnaise + fava bean, broken	15	No	9	7.8	Abdel-Haleem et al. (2022)
Mayonnaise + white bean, broken	15	No	9	7.2	
Mayonnaise + cowpea, broken	15	No	9	7.6	

Note: For food made with different levels of enrichment, the average value was reported.
[a]Abbreviations: CWa, cooking water; OA: overall acceptance.

untrained panelists. Sensory descriptive analysis and consumer acceptability testing (hedonic or affective tests) are the most common methods of sensory evaluation (Yang & Lee, 2019). Table 5 provides an overview of the sensory evaluation of foods enriched with different percentages of pulse byproducts using the mean values of consumer overall acceptability. The food products that have been analyzed include bread, bakery products, pasta, soup, beverages, and meat products. The assessment was based on hedonic scales with 9, 8, or 5 points, and 10–140 trained and untrained judges. Importantly, most of the studies recruited < 40 untrained judges, which does not comply with the sensory analyses good practices. Among all examined products, bread and bakery goods showed the highest overall acceptability. The use of 0.5% black bean extract in bread was better appreciated (Chávez-Santoscoy et al., 2016) than extracts of pea and broad bean pods (Belghith-Fendri et al., 2016b). In the process of snack preparation, the replacement of wheat flour with 5%–15% dehydrated green curd of pea peel flour demonstrated the highest mean overall acceptance of 8.4 on a 9-point hedonic scale (Mousa et al., 2021). The replacement of wheat flour with a greater percentage of pea pod powder in the bakery products resulted in lower consumer acceptance, probably due to the green color caused by the presence of chlorophyll (Belghith-Fendri et al., 2016a). Cakes containing 5%–30% pea pod or broad bean pod powder reached 3.1 and 3.0 points on the 5-point hedonic scale, respectively. The incorporation of 15%–30% broken whole black beans in cookies achieved 6.21 points, whereas the addition of 15%–30% broken peeled black beans achieved 5.74 points on the 9-point hedonic scale.

The enrichment of soup with pea peels was more favorable (Mousa et al., 2021), compared to the addition of pea pod powder (Hanan et al., 2020). Chicken nuggets containing 5%–10% chickpea hull flour scored lower (6.5 points) than those containing 8%–12% pea hull flour (6.9 points) on the 8-point scale (Arun K. Verma et al., 2012, 2015). The decline in the acceptability of chicken nuggets when the percentage of chickpea or pea flour was increased probably reflects the slight grayish color of chickpea hull flour and the presence of dark granules in pea hull flour. Mayonnaise enrichment with pea pod powder showed a promising score of 8.2 on the 9-point scale (Rudra et al., 2020), whereas the addition of broken fava bean, white bean, and cowpea powder was less favorable (Abdel-Haleem et al., 2022). The effect of product color on consumer evaluation is still contested (Fernández-Vázquez et al., 2013; Spence, 2015, 2019). The proper balance of nutritional profile and sensorial evaluation is an essential aspect for the development of novel functional foods enriched with a wide range of pulse byproducts.

10 | NETWORK ANALYSIS

Correlation-based network analysis (Figure 3) allowed us to detect correlations between the nutritional, techno-functional, and sensorial properties of ingredients from agricultural byproducts. Nutritional properties comprise six nodes and are represented by the content of protein, lipids, resistant starch, total phenolic content, total carbohydrates, and total dietary fiber. Techno-functional properties comprise eight nodes and are characterized as chewiness, springiness, hardness, color coordinates (L*, a*, b*), adhesiveness, and cohesiveness. Sensory features comprise seven nodes defined as color, taste, appearance, flavor, odor, texture, and overall acceptance. In total, the network is composed of 21 nodes and 52 edges. We observed high connectivity within the group of sensorial characteristics. Nutrition, techno-functional, and sensorial parameters showed more interactions with other groups than within the same group of features. Identified correlations within the same group of features were found to be mainly positive. Indeed, 79% of all connections were positive. Previous studies suggested that food enrichment with healthy functional ingredients often had a negative effect on parameters representing techno-functional properties (Godswill et al., 2019). Nevertheless, the network showed five positives out of seven identified links between nutritional and techno-functional characteristics. Nutritional properties showed 83% positive correlations (5 of 6) with sensorial features and 71% (5 of 7) positive correlations with techno-functional parameters. Techno-functional parameters, in turn, exhibited seven positive and six negative correlations with sensorial traits. As expected, overall acceptance of the final product was connected positively with appearance (0.73), flavor (0.4), odor (0.43), taste (0.49), and texture (0.49). Protein content was linked negatively to the product color (L*) and positively influenced the level of lipids, odor, and total carbohydrates. Total carbohydrates negatively affected cohesiveness (−0.33). Resistant starch interacted positively with springiness (0.54), which is associated with fresh high-quality products (Sanz et al., 2009). Previous studies reported that TDF, although considered beneficial for health, could negatively affect product characteristics such as texture, flavor, color, and appearance (Escobedo & Mojica, 2021). Additionally, TDF was found to be positively correlated with springiness and adhesiveness (Javanmardi et al., 2021). Our observations are partially supported by previous findings, revealing positive connections between TDF and springiness (0.62) and adhesiveness (0.37). We also observed positive correlations between TDF and sensorial parameters such as odor (0.3) and taste (0.31). The lipid content was linked positively to flavor (0.31). Volatile compounds defining flavor can be synthesized from free fatty acids through the lipase-dependent pathway in model plants such as *Arabidopsis thaliana* (Mwenda & Matsui, 2014) and tomato (Garbowicz et al., 2018; Kuhalskaya et al., 2020). As shown in a previous study (Comunian et al., 2021), phenolic compounds in food matrices may cause astringency, which influences the sensory perception of many foods and beverages, ranging from wine to nuts (Bajec & Pickering, 2008). Our results indicated that the TPC negatively affected overall acceptance (−0.31). Chewiness showed a positive correlation with springiness (0.35), and a strong positive correlation with hardness (0.85), whereas hardness interacted negatively with color (−0.29). The product texture was positively connected with cohesiveness (0.4), springiness (0.31), color (0.36), flavor (0.83), chewiness (0.35), appearance (0.37), and the overall acceptance (0.49) of the final product.

11 | GENETIC RESOURCES

Plant genetic resources provide a fundamental reservoir of genetic diversity that can be exploited in breeding programs to develop varieties with improved traits, such

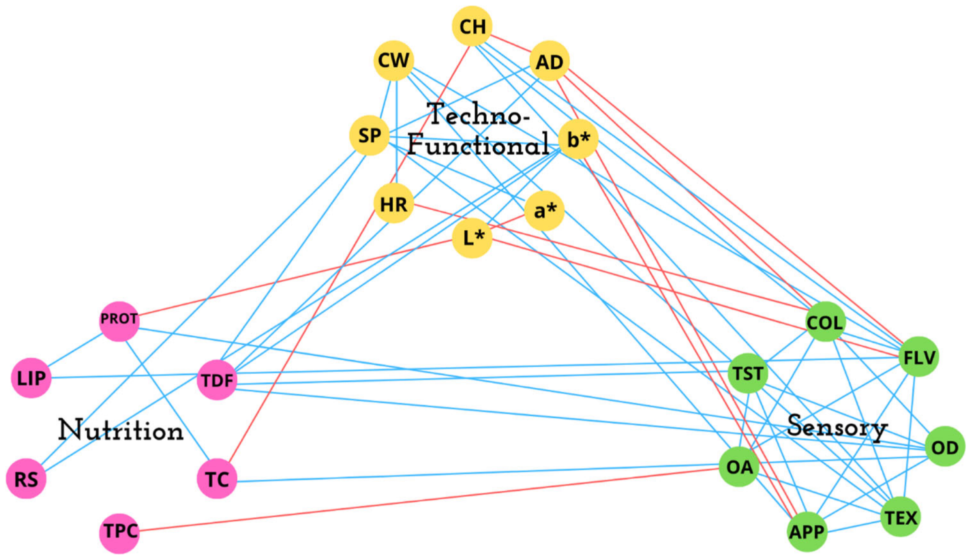

FIGURE 3 Pearson's correlation ($p < .05$) based on data from Tables 1, 2, 4, and 5. Each node represents a distinct feature: nutrition (RS = resistant starch; LIP = lipids; PROT = proteins; TDF = total dietary fiber; TC = total carbohydrates; TPC = total phenolic content), functional (SP = springiness; HR = hardness; CW = chewiness; CH = cohesiveness; AD = adhesiveness; L*, a* and b* = color coordinates) and sensory properties (OA = overall acceptance; TST = taste; COL = color; FLV = flavor; OD = odor; TEX = texture; APP = appearance) of the final products (bread, bakery, pasta, soup, beverages, meat products, and mayonnaise). Edges connecting two nodes show an association between two parameters: blue represents positive correlations; red represents negative correlations. In total, the network is composed of 21 nodes and 52 edges assembled into three groups: nutrition properties comprise of six nodes, techno-functional parameters have eight nodes, and sensory features have seven nodes.

as adaptation, agronomic features, and nutritional quality. Crop genetic resources and their level and structure of genetic diversity are the results of evolutionary processes, such as domestication far beyond the areas of origin, adaptation to different agro-environmental conditions, and modern breeding. Domestication is one of the main evolutionary events that affected the genetic diversity of crops and significantly improved the quality of human diets. Over the years, domesticated crops have lost several features from their wild ancestors, while characteristics that meet human needs (such as high grain yield and good quality) have been accumulated and strengthened (X. Chen et al., 2021; Meyer & Purugganan, 2013). In a few cases, related to nutritional traits, the opposite may have occurred (Beleggia et al., 2016).

Legume crops can play a key role in food security and human health by mitigating climate change and increasing sustainability (Bellucci et al., 2021; Mudryj et al., 2014). At the same time, the increased consumption of legumes as an alternative source of protein has increased the accumulation of byproducts such as seed coats, pods, and broken seeds (Prandi et al., 2021). Among the traits that improve the nutritional quality of legume seeds, several are important for the use of byproducts too. For example, the seed coat is a major legume by-product that has a high content of dietary fiber, minerals, and phytochemicals that make it suitable as a food ingredient (Zhong et al., 2018). The TPC of the seed coat is up to eight-fold higher than that of the whole seed, and the diversity of phenolic compounds is greater, including those recognized as major antioxidants (Dueñas et al., 2006; Oomah et al., 2011). Seed coat color can provide a useful marker of the TPC, given that the hull of green lentils has a significantly higher TPC than that of red lentils, thus providing greater antioxidant activity (P. X. Chen et al., 2015). Pod shattering is a trait that has been partially or completely lost during legume domestication (Di Vittori et al., 2019). Non-shattering phenotypes are preferred because pod shattering is responsible for crop losses, but there is a strong positive correlation between pod shattering and the pod fiber content (Di Vittori et al., 2021; Murgia et al., 2017). Domestication also affected the nutritional composition of legumes (Kerem et al., 2007). In lupin, for example, domestication and breeding depleted the alkaloid content of seeds (Kroc et al., 2017). Understanding the nutritional quality of legume genetic resources by analyzing them at traits responsible for the favorable nutritional profile of byproducts, allowing their use as food ingredients, can benefit human health and also make legume cultivation and consumption more environmentally friendly for the European agricultural system. A detailed analysis of the genetic diversity of nutritional traits in food-legume genetic resources could therefore facilitate the development of innovative food products that highlight the relevance of both main products and byproducts (Bellucci et al., 2021; Katuuramu et al., 2018; Murube et al., 2021; Summo et al., 2019).

12 | CONCLUSION

A circular economy approach is necessary to reduce the quantity of waste from the legume production chain, and could also deliver healthy and highly nutritious techno-functional ingredients such as flours, protein/fiber fractions, extracts, and cooking/soaking water. Legume byproducts have been extensively used in baked goods, but their versatile techno-functional properties make them suitable for many other food applications, including healthy beverages, vegan dressings with a longer shelf life, and the development of ingredients with useful techno-functional properties such as foaming and emulsification, reflecting the enrichment of polyphenols extracted from legume byproducts. The correlation-based network showed promising interactions between nutritional properties, techno-functional parameters, and sensorial features of the final food that might be useful for the further improvement of ingredients derived from legume byproducts.

Consistent data were found in previous studies regarding the evaluation of techno-functional properties. This may help to predict the behavior of ingredients in different food systems, leading to innovative high-quality foods that meet consumer demands. Nevertheless, the variability of the units used to express techno-functional properties (solubility, water binding capacity, viscosity) makes it difficult to achieve a reliable comparison given that conversions could be a source of errors. Concerning sensory acceptability, improved methods targeting product appearance and flavor enhancement should be developed to keep consumers interested. One limitation is the non-compliance of most research with the sensory analyses good practices. More judges are needed to increase the consistency of such analysis.

Although legume byproducts are rich in bioactive compounds, antinutritional factors can reduce the absorption of essential nutrients. Moreover, clinical trials, as well as in vitro and in vivo studies, are required to validate the health benefits of ingredients based on legume byproducts. The digestibility of the proteins should be addressed given the effect of antinutritional factors on human health. The articles considered here did not provide extensive data concerning the antinutritional factors present in legume byproducts. FODMAPs should be discussed because they are likely to dissuade consumers from trying foods containing legume byproducts. A deeper exploration of eco-friendly techniques (e.g., fermentation and ohmic treatment) is necessary to improve the techno-functional properties of ingredients, increase the bioavailability of bioactive compounds, reduce the content of antinutritional factors, and enhance the sensory characteristics of the final foods. The combination of legume by-product processing technology and improved legume genetic resources could enhance the nutritional, functional, and technological properties of formulations to allow the industrial production of legume-based foods that are acceptable to consumers. However, food safety assessment for antinutritional factors and validation of the health effect of functional foods should be investigated in more detail to ensure the full exploitation of ingredients containing legume byproducts.

AUTHOR CONTRIBUTIONS

Ancuta Nartea: Project administration; Visualization; Writing-original draft. **Anastasiya Kuhalskaya**: Data curation; Formal analysis; Visualization; Writing-original draft. **Benedetta Fanesi**: Data curation; Visualization; Writing-original draft. **Oghenetega Lois Orhotohwo**: Data curation; Visualization; Writing,-original draft. **Karolina Susek**: Writing-review & editing. **Lorenzo Rocchetti**: Writing-review & editing. **Valerio Di Vittori**: Writing-review & editing. **Elena Bitocchi**: Writing-review & editing. **Deborah Pacetti**: Conceptualization; Supervision. **Roberto Papa**: Funding acquisition; Writing-review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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