Legume Consumption

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Legumes are nutrient-dense crops with health-promoting benefits. However, several barriers are associated with their consumption. Emerging issues including food neophobic tendencies or taboos, unclear dietary guidelines on legume consumption, health concerns, and socio-economic reasons, as well as long cooking procedures, adversely affect legume consumption frequency. Pre-treatment methods, including soaking, sprouting, and pulse electric field technology, are effective in reducing the alpha-oligosaccharides and other anti-nutritional factors, eventually lowering cooking time for legumes.

diet cooking legumes consumption intake nutrient profile health effects

1. Introduction

The world population is constantly growing, and the current global population of 8 billion (as of mid-November 2022) is expected to increase to 9.7 billion in 2050 [1]. Increased population pairs with a predicted higher demand for food. Total food demand, including that from protein sources, is expected to increase from 35% in 2010 to 56% in 2050 [2]. In the past decade, consumers' interest in increasing protein intake from alternative sources, including plant-based types such as legume-derived ones, has increased. This request has been driven by factors including the relatively lower carbon footprint associated with leguminous crop cultivation, with its fewer deleterious effects on climate change compared to cattle breeding [3][4][5], health reasons [3][5], and the relatively high cost of meat compared to legume-derived proteins [6], especially in Southeast Asia and Sub-Saharan Africa. Moreover, the increased sustainability associated with the production of plant crops, including legume proteins, should be taken into account [7][8]. Globally, different legume types are widely distributed.

The Food and Agriculture Organization of the United Nations (FAO) recognizes ten main types of legumes: dry beans including soybean, dry broad beans, dry peas, chickpeas, cowpeas, pigeon peas, lentils, Bambara beans, vetches, and lupins [9]. Additionally, there are "minor" legumes that are less commonly used internationally [9]. The four most commonly used species for food purposes, marketed in both dry and hydrated forms, are beans, lentils, peas, and chickpeas. Leguminous crops are resilient towards climate changes and possess an inherent ability to fix atmospheric nitrogen in the soil leading to improvement in soil fertility [10]. In terms of nutritional composition, legumes contain a high concentration of protein (23.7–25.9 g/100 g dry beans and 8.23–9.01 g/100 g for cooked beans), a high content of soluble and insoluble fibers (4.1–4.3 g/100 g dry beans and 7.0–10.5 g/100 g for cooked beans), a low lipid content (except for soybeans), are free of saturated fats and cholesterol, and are good sources

of B-group vitamins, iron, magnesium, copper, selenium, calcium, potassium, zinc, and manganese [11][12]. Legumes generally have a low caloric density and low glycemic index, due to their high fiber composition [12].

According to European and American nutritional guidelines, legumes are an important part of a healthy diet [13][14]. The European Food Safety Authority [15] states that legumes represent a valid source of protein and that they are essential for a healthy diet. It has been recommended that adults consume at least 20–25 g of protein from plant sources per day [13]. Due to the excellent nutritional profile and health-promoting effect associated with legume consumption, they represent an important component of several dietary guidelines. For example, increased consumption of legumes has been encouraged as part of the Mediterranean and the DASH dietary pattern guidelines. Several epidemiological studies demonstrated improved outcomes in cardiovascular disease, diabetes, cancer, Alzheimer's disease, and Parkinson's disease following strict adherence to the Mediterranean and DASH diet, both including legumes [16]. The DASH diet recommends an intake of about four-to-five servings of legumes per week for a 2000-calorie diet to effectively control blood pressure [17]. Additionally, the 2020–2025 Dietary Guidelines for Americans recommend legumes as part of a healthy dietary pattern, stating that "legumes provide protein, dietary fiber, and a variety of vitamins and minerals, including iron, potassium, and folate" [14]. Legumes are a healthy and versatile food option for people following specific diets, such as those for people with gluten intolerance [18] or vegetarianism [19]. This has been largely attributed to their gluten-free nature [20]. Furthermore, legumes combined with cereals provide all of the essential amino acids and represent a valuable one-dish meal for vegans or vegetarians. Legumes are thus used in complementary formulations in cereal-based products, due to their high amino acid lysine content which in cereals is deficient [21].

Hughes et al. [22] recently showed that there was a general global decline in beans and legume consumption, according to data derived from the Global Dietary Database ("GDD 2018") in June 2022. The authors evaluated the national intake of legumes and beans considering the 50 g/day [23][24] target, which has been established according to several meta-analyses as the ideal intake required to reduce mortality and morbidity outcomes [23][24]. The general decline observed could be attributed to the lack of clear recommendations on the appropriate quantity and serving size of beans and other legume-based products despite the availability of national food-based dietary guidelines, as observed in Australia [25]. This is because most of the food-based dietary guidelines group together legumes with seeds, vegetables, and starchy staples [25]. In a recent cross-national survey conducted in Europe, consumers from Poland, Spain, and Germany reported that digestion challenges associated with legume consumption were an important barrier that restricts legume intake. In Danish and UK consumers, the lack of available easy-to-cook legume and legume-based products was the underpinning barrier to their consumption [26]. Consequently, there is a need to implement strategies that could promote legume intake in the population. This could lead to improved health outcomes and increased sustainable food supply, resulting in a lower carbon footprint and leading to better environmental sustainability. In 2015, Polak et al. [27] reviewed the health effects and some culinary approaches that could be adopted to promote legume consumption. However, barriers and strategies to improve digestibility and overcome digestive challenges associated with legume intake, leading to increased consumption, have not been addressed. The present article therefore highlights the effects of cooking on the nutritional profile of legumes, underlines health effects associated with legume consumption, and, finally, examines strategies to improve the digestibility and nutritional profile of legumes. Additionally, the use of state-of-

the-art educational and culinary approaches that could be exploited to improve legume intake are extensively discussed.

1.1. Nutritional Composition of Commonly Consumed Legumes

The nutritional composition of legumes influences their health-promoting properties, which is an important factor that can influence consumers' consumption of legumes. Legumes are rich in protein and fiber. For example, according to the USDA Food Data Central database, protein and fiber content ranging from 19.0 to 36.0 g/100 g and from 9.0 to 25.0 g/100 g, respectively, for legumes including common beans, lentils, chickpeas, peas, broad beans, and soybeans have been reported [28].

The high protein content of legumes is a promising trait that makes them ideal candidates for product reformulation with foods that are generally lower in protein. It is important to note that protein addition would influence aliment techno-functional and sensorial properties when used in food product development. Although plant-based proteins are deemed second-class proteins, efforts to improve their digestibility could enable them to compete with those derived from animal sources. The relatively high fiber content [28] makes them promising for lowering the glycemic impact of foods when incorporated into other staple foods and could induce satiety. The cooking of legumes is essential as it impacts its digestibility and nutritional composition [29]. Storz et al. [30], recently, using a nationally representative sample of 9078, investigated the current sex distribution of cooking responsibilities in the United States of America. The authors reported that cooking duties are still being mostly performed by women. Consequently, women could be targeted for educational training efforts to promote legume consumption. The effect of cooking methods on the nutritional composition of some commonly consumed legumes will be discussed.

Margier et al. [31] investigated the effect of household cooking and canning on the nutrient profile of common legumes including kidney beans, white beans, chickpeas, and brown and green lentils. For the household cooking employed, the authors adopted household cooking methods protocol established by the French National Federation of Dry Legumes. The legumes were soaked in low-ionized water overnight at room temperature using a water-to-legume ratio of 5:1, with the exception of lentils. The legumes were drained of the water and cooking proceeded afterwards using a water-to-legume ratio of 2:1. Cooking duration was 25 min, 1 h 30 min, and 2 h for the lentils, kidney beans/white beans, and chickpeas, respectively. In the canning process, the pre-treatment method, which involved an overnight legume soaking in water at a ratio of 1:3, was employed. Blanching legumes at 90 °C for 5 min was carried out prior to transfer into a can with hot brine at a ratio of 195/236 (*w*/*w*). Sterilization of the legumes was carried out at 127 °C for 16 min in the can. The final step involved the cooling of the sterilized products to a temperature of 30 °C for 10 min. The authors stabilized the sterilized legumes by draining the water, rinsing the legumes in water, and subsequently freezing the legumes. The samples were freeze-dried and kept at a temperature of −80 °C until analysis. The results showed a general increase in the protein and fiber content of all the legumes cooked using the household cooking method compared to the canning method. Specifically, the protein and fiber content of kidney beans, white beans, chickpeas, and lentils increased by 30.30 and 43.97%, 17.78 and 33%, 17.44 and 21.95%, and 38.87 and 55.29%, respectively, when the household cooking method was used, compared to the sterilization process [31]. The general decrease in protein concentration of the cooked

legumes compared with the raw types could be attributed to the loss of proteins into the cooking water, which could be considered part of the cooking losses.

1.2. Bioactive Properties of the Minor Components of Legumes

Legumes, aside their rich nutrient profile, contain bioactive compounds that provide favorable health effects [32]. Bioactive compounds are mainly secondary plant metabolites that are synthesized by the plants to enable them to defend themselves from predators [33]. In legumes, bioactive compounds and other compounds are present as minor components and include polyphenols, saponins, enzymes inhibitors, and phytates (**Figure 1**). The bioactive compounds that are present in legumes provide favorable effects on health [34]. Consequent to this, legumes can be considered as “functional foods”, due to the presence of nutrients and bioactive compounds. Examples of bioactive compounds present as minor components of legumes and their potential health-promoting properties have been highlighted (**Figure 1**).

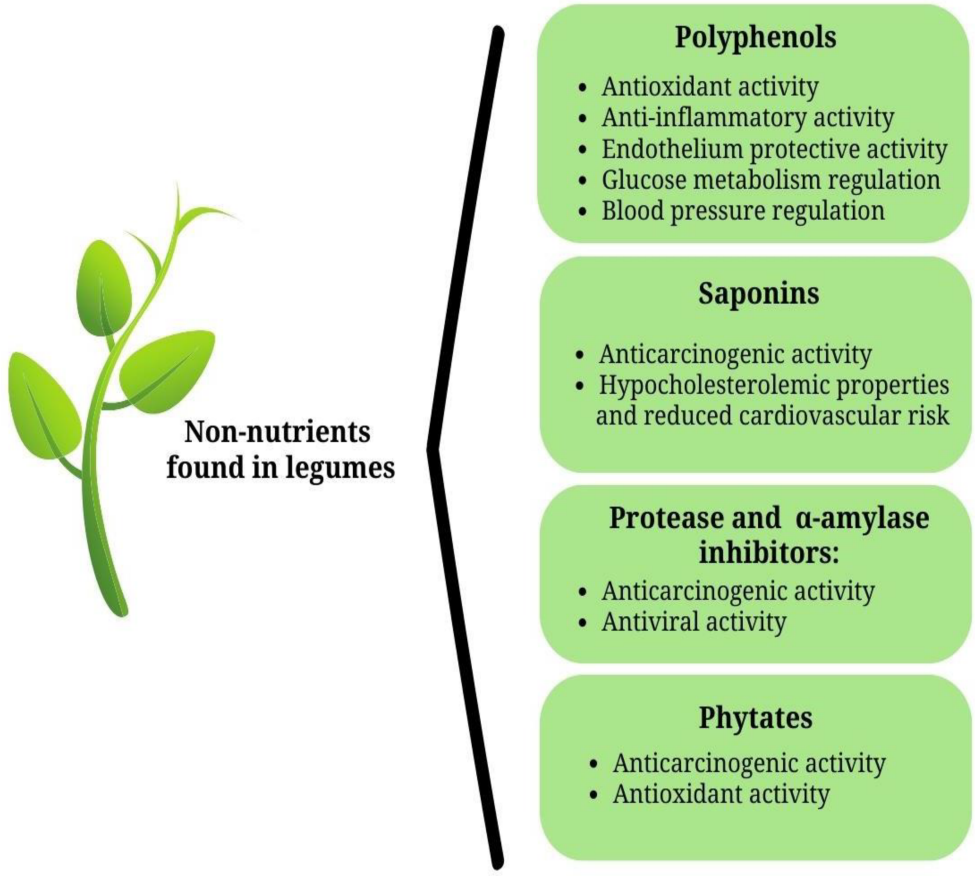


Figure 1. Biological activity of the minor components of legumes. The figure shows the biological activity of the minor components of legumes and their potential health effects.

2. Health Effects Associated with Legume Consumption

2.1. Effect on Cardiovascular Diseases

Recently, several systematic reviews and meta-analyses of prospective studies have established an inverse association between increased legume intake and cardiovascular (CVD) risk and its disease outcomes [35][36]. For example, increased consumer intake of legumes (≥50 g/day) was associated with a lower risk of coronary heart disease [23] and strokes [36]. CVD, A 6% decrease in CVD risk was associated with increased legume consumption [35]. The plausible reason associated with the improved CVD and coronary artery disease (CAD) outcomes following increased legume consumption could be attributed to the modulation of total cholesterol and low-density lipoprotein cholesterol (LDL-C) blood levels [37], which represent well known risk factors for CVD and CAD. The mechanisms of protection can be explained since fibers, particularly the soluble type from legumes, prevent bile acid recycling as bile acid is removed from the body through feces [38]. This subsequently increases the rate of cholesterol conversion into bile acids and results overall in lower cholesterol concentrations in the body. The second mechanism could involve the role of saponins in the legumes on the modulation of cholesterol levels. Saponins are secondary plant metabolites produced by legumes to provide defense against predatory attacks. Due to their intrinsic presence in legumes, upon legume consumption saponins are hydrolyzed by intestinal bacteria to form an insoluble complex. Saponin complexes interact with cholesterol molecules, impairing the formation of micelles, inhibiting lipase enzyme, and chelating bile acids with subsequent reduction in circulating cholesterol concentration through increased cholesterol conversion into bile acids [39]. Another mechanism could involve the production of short-chain fatty acids, including propionic and butyric acid, as a result of the fermentation of resistant starches from legume fibers [40]. Short-chain fatty acids (SCFAs) have been shown to inhibit hepatic cholesterol synthesis in animal models [41]. A relatively lower production of trimethylamine N-oxide (TMAO) by the gut microbiota following legume consumption was observed, as earlier reported, in comparison to animal-based protein sources deriving from fish or red meat [42][43]. The presence of trimethylamine N-oxide (TMAO) levels in the blood and urine has been established as an objective biomarker associated with increased risk of heart disease. The presence of specific concentrations of micronutrients, including low sodium, high magnesium, and potassium in legumes, may contribute to the reduction of arterial hypertension risk [44]. Legumes are low glycemic index foods with potential insulin-sensitizing effects [45][46][47]. Insulin inhibits the release of free fatty acids from adipose tissue, and this makes legumes impact positively on VLDL and LDL levels [48][49].

2.2. Effects on Diabetes Risk

Legumes, due to their high fiber and resistant starch content, are effective in controlling postprandial glucose levels and insulin response when compared to other carbohydrate-containing foods [50]. Fiber increases satiety and decreases the absorption efficiency of fats and carbohydrates [51]. Soluble fiber reduces peak blood glucose because it increases the viscosity of the intestinal contents and hinders the absorption of monosaccharides [52], while insoluble dietary fiber modulates the release of gastric hormones and causes delayed absorption of monosaccharides [53].

Dietary plans involving the use of legumes in the medium to long term are desirable in individuals with type 2 diabetes mellitus due to their efficacy in controlling glycemic markers; however, in non-diabetic individuals, individuals with type 1 diabetes, and individuals with prediabetes, the evidence is still limited or contradictory and requires further long-term randomized controlled trials [54][55]. It has been observed that regular consumption of

legumes may play an important role in reducing the risks associated with type 2 diabetes mellitus. In a recent systematic review of randomized, controlled trials [56] of individuals with and without diabetes, statistically significant effects were observed in the groups of subjects consuming diets high in legumes with regard to reductions in fasting blood glucose, glycosylated hemoglobin, and blood glucose two hours after a meal. In subjects with type 1 diabetes, the only statistically significant effect found was the decrease in blood glucose two hours after the meal. Improvements in glycemic control were consistently observed on the legume diet in diabetic individuals in several studies identified by this research. Diets containing legumes have also been associated with lower postprandial insulin levels [57]. Several studies [58][59] have also evaluated the effects of legume consumption on the risk of gestational diabetes. Pregnant women may benefit from a legume-based diet to prevent gestational diabetes [58]. Women who adopted a plant-based diet during pregnancy had a significantly reduced risk of developing gestational diabetes compared to women who followed a standard diet [59].

2.3. Effects on Overweight and Obesity

Due to their particular nutritional characteristics (high fiber and protein content, low glycemic index, low fat content), legumes can be considered a useful food to treat and prevent obesity and being overweight [60]. There are several mechanisms that can explain the weight loss associated with legumes. Some of their satiating properties can be attributed to the presence of fiber, which increases chewing time, delays gastric emptying, inhibits food intake, and stimulates early satiety signals. In addition, soluble fiber in the gastrointestinal lumen forms viscous gels that slow the passage of food through the digestive tract, contributing to the feeling of fullness [61]. The high protein content stimulates the secretion of the hormones cholecystokinin and GLP-1, which contribute to increased satiety [62]. The low glycemic index regulates the secretion of insulin and the blood concentration of glucose, thereby controlling the desire to eat. In addition, legumes contribute to weight loss through the reduced bioavailability of nutrients. High-fiber diets contribute to reduction in fat and protein absorption by reducing the physical contact of nutrients with the intestinal villi [61], by limiting intestinal absorption of nutrients through the formation of viscous gels due to soluble fiber, and by increasing intestinal transit speed due to insoluble fiber [63]. Another characteristic that contributes to making legumes appropriate aliment in weight loss diets is the quality of the carbohydrates: these foods contain a high quantity of amylose-type starch which, after cooking, undergoes the process of retrogradation and becomes more resistant to digestion, compared to amylopectin-type starch [64]. All these mechanisms involving fiber and resistant starches act synergistically to increase satiety, manage body weight, reduce glycemic response, and improve insulin sensitivity [65]. Cell-wall polysaccharides, oligosaccharides (raffinose, stachyose, and verbascose), and resistant starch are the main non-digestible carbohydrates in legumes that are fermented by intestinal bacteria into SCFAs, which are able to influence lipid metabolism and promote fat oxidation and energy expenditure [66].

2.4. Effects on Certain Types of Cancer

Some studies have linked the consumption of legumes with a protective effect on certain types of cancer, such as colon, prostate, and breast cancer [67]. According to the World Cancer Research Fund/American Institute for Cancer Research [68], the high amounts of vitamins and minerals in legumes have been suggested to reduce the risk of developing cancer. In vivo studies with rats, in which pre-neoplastic lesions were caused by azoxymethane,

showed that eating beans was associated with a lower risk of colon cancer [69]. Similar studies have been conducted to evaluate the effect of bean consumption on induced breast carcinogenesis in rats [70][71]. In the groups that consumed beans, there were dose-dependent reductions in the incidences of breast cancer compared to the control group. In addition, a dose-dependent reduction in the blood concentration of glucose, IGF1 (insulin-like growth factor), C-reactive protein, IL6, and increased apoptosis in mammary adenocarcinoma cells were found in the treated group.

The non-digestible fraction (resistant starch, insoluble fiber, and oligosaccharides) of many types of common beans possesses anti-proliferative activity and is able to induce apoptosis in colon cancer cells [34]. There are several micronutrients that contribute to the possible anti-cancer effect of legumes: trace elements such as zinc, which is associated with a reduction in oxidative stress and improved immune system functioning, and selenium which, due to its ability to inhibit the development of tumor cells in mouse models of cancer, could play a role in the prevention of breast, esophageal, and stomach cancer [43]. Saponins, protease inhibitors, phytates, and tannins appear to have anticarcinogenic activity due to their antioxidant and regulatory action on cell proliferation [72][73]. Protease inhibitors slow down the rate at which cancer cells divide and stop proteases, which kill nearby cells, from being released. Specifically, black beans contain a trypsin inhibitor that possesses anti-proliferative activity in vitro [74].

2.5. Prebiotic Potential

The high amounts of non-digestible oligosaccharides (raffinose, stachyose, and verbascose), resistant starch, and other non-starch polysaccharides in legumes contribute to the formation of SCFAs in the large intestine. This confers to these foods “prebiotic potential” by changing the composition of the intestinal microbiota and increasing the growth of Bifidobacteria. Among the short-chain fatty acids, in particular propionate, has been shown to decrease cholesterol levels, reduce endogenous fatty acid synthesis, and promote satiety [66]. SCFAs can influence enterocyte growth because butyrate is their main source of energy and appears to protect against cancer with anti-inflammatory and anti-tumor effects on colon cancer cells, and also affects mineral availability because a lower pH in the colon allows calcium and magnesium to dissolve more easily [75]. To figure out if a diet high in legumes can change the gut bacteria in a good way, more research needs to be carried out to investigate their prebiotic potential.

2.6. Oxidative Stress and Inflammation

Since oxidative stress and inflammation are recognized as playing crucial roles in the onset of age-related and chronic diseases, they may be fruitful dietary targets for preventing illness [76]. Legumes contain polyphenols in the form of phenolic acids and flavonoids, which have anti-inflammatory and antioxidant properties and protect tissues from oxidative stress. Flavonoids counteract free radicals, endothelial dysfunction, and platelet aggregation [77]. The intake of legumes four times a week in a nutritional plan against obesity with a moderately low-calorie diet resulted in a decrease in lipid-associated oxidative stress with a decrease in lipid peroxidation biomarkers, such as oxidized LDL and malonylaldehyde, and also in C-reactive protein, independent of weight loss [78].

3. Barriers towards the Consumption of Legumes

Several factors impact consumption of food crops including legumes. In the case of legumes, despite their rich nutritional and health-promoting properties, analysis of their consumption using data from the Global Dietary Database (GDD 2018) in June 2022 showed a general global decline in beans and legume consumption [22]. The decline in consumption was more prominent in several high-income countries including the United States of America and Canada. In that same study, the authors compared the national legumes and beans consumption with the 50 g/day target which has been established in several meta-analyses to be the intake required to reduce mortality and morbidity outcomes [22]. The general decline observed was attributed to factors including the lack of clarity regarding the quantity and serving size of beans and other legume products despite the availability of national food-based dietary guidelines. Additionally, most of the food-based dietary guidelines group legumes with seeds, vegetables, and starchy staples. Consequently, due to the aforementioned challenges in Australia, consumers declared that the use of the statement “each day, consume at least one serving of legumes either as a serve of vegetables or as an alternative to meat” was enough to compel them to increase their consumption of legumes [25].

3.1. Phychosocial and Socio-Economic Reasons

3.1.1. Food Neophobia Tendencies

Food neophobia is a dietary behavior associated with the lack of desire for a consumer to taste new food products or other unfamiliar food products [79]. The drivers of this could be attributed to perceived unappealing organoleptic attributes of the food, health complications due to allergy-triggering tendencies, and traditional beliefs. Legumes exist in different forms apart from the other well-known types including chickpea, soybean, cowpea, and lentils. Consumers used to one type of legume are reluctant to try new ones. In Ghana, for example, although there are now efforts to promote the consumption of other uncommon legumes such as the broad bean types, consumers appear to have an apathy towards consuming these legume types. Karaağaç et al. [79] suggested that educational programs and activities related to food in order to promote positive attitudes and experiences towards food could be an efficient and promising tool to overcome food neophobia tendencies and could subsequently result in improved consumer interest in tasting familiar and unfamiliar foods.

3.1.2. Food Taboos

Food taboo is another important factor that promotes the lack of interest in legume consumption. It results in nutritional deficiencies and adversely affects the nutritional status of consumers. Meyer-Rochow et al. [80] have extensively reviewed food taboos amongst different religious and geographical orientations. Food taboos connote restrictions toward the consumption of certain food types, driven mainly by religious doctrines and traditional beliefs [80]. This practice is common in several low- and middle-income countries, including in Africa. For example, recently, a cross-sectional study involving 332 pregnant women was conducted in Ethiopia to investigate food taboos and other related misperceptions [81]. The authors reported that 45.7% of the pregnant women reported the consumption of legumes as a food taboo. The women reported that factors including development of abdominal

cramps, prolongation of labor with subsequent trigger of pain sensations, and possible abortion induction were the predominant reasons to avoid beans and chickpea intake.

3.1.3. Socio-Economic Factors

Over the last thirty years, the revolution in eating habits in industrialized countries has led to the need and desire, for economic and social reasons, to spend less time on food preparation in the kitchen. In fact, most grain legumes, when not purchased already cooked, require long processing and cooking times that may discourage their use. Changes in lifestyles, less time available for cooking, the greater availability of affordable processed foods that require less time to prepare, and greater commercial pressure have led in some southern European countries (Italy, Greece, Portugal) to a gradual abandonment of the so-called Mediterranean diet, based on the intake of products such as vegetables, fruit, whole cereals, legumes, oil seeds, dried fruit, extra virgin olive oil, fish, and wine, and to an increase in the consumption of processed and refined foods and sugary drinks [82]. The same trend is being observed in many Latin American countries, traditionally large consumers of pulses, where rapid urbanization and socio-economic changes have caused changes in their eating habits [83].

3.2. Digestibility and Health-Related Concerns

Legumes, despite their rich nutritional profile, contain other compounds including non-digestible carbohydrates, such as alpha-galactosides and anti-nutrients that could impair human health, as their presence in legumes can cause nutritional deficiencies by limiting protein digestibility, the bioavailability of minerals and vitamins, and altering the intestinal epithelium [84]. Oligosaccharides, such as raffinose, stachyose, and verbascose, which are a class of carbohydrates referred to as alpha-galactosides, are intrinsically present in legumes although their concentration varies depending on the species of legume consumed.

Consequently, these carbohydrates reach the colon undigested, where they undergo an anaerobic fermentation process by the intestinal microbiota, resulting in the formation of SCFAs and gases (hydrogen, carbon dioxide, and methane) responsible for bloating, distension, abdominal pain, and diarrhea [85]. Flatulence is one of the factors that make legumes unacceptable in the diets of western countries and discourages their use. A high raffinose content in the diet (>6.7%) has osmotic effects in the intestine and contributes to the onset of diarrhea, along with excessive fermentation [75]. The osmotic pressure imbalance generated in the small intestine by oligosaccharides of the raffinose family reduces its absorption capacity. It has been established through in vivo studies that the presence of lupin oligosaccharides in the intestinal mucosa reduced the efficiency of protein digestibility. However, the extraction/elimination of these compounds from lupin resulted in significant increase in all lupin amino acids using pig models [75]. Furthermore, these oligosaccharides appear to be implicated in the increasing susceptibility to chronic gut diseases such as Crohn’s disease and, especially, irritable bowel syndrome, in which they are considered irritants [86]. Finally, studies have shown that alpha-galactosides are responsible for decreasing the net energy content of the diet [75].

Anti-nutrients are another class of compounds in legumes that impair the digestibility of proteins, and the bioavailability and bioaccessibility of minerals and vitamins [84]. This subsequently results in nutritional deficiencies

in the body. They also alter the intestinal epithelium [84]. Most of the anti-nutritional factors have important physiological functions and are indispensable for the plant's defense mechanisms; therefore, it is not possible to remove them from seeds during cultivation, as this would be incompatible with agronomic requirements. Examples of some commonly reported anti-nutrient compounds in legumes include protease inhibitors, lectins, phytic acid, oxalate, and saponins.

Protease inhibitors reduce trypsin and chymotrypsin activity, resulting in impaired protein digestion [87]. They have also been associated with growth inhibition and pancreatic hypertrophy in certain experimental animals [88]. Alpha-amylase inhibitors have also been associated with an increase in pancreatic hypertrophy [89]. They form a complex with amylase, reducing its activity and resulting in reduced starch digestion [64].

Lectins are present in many bean species; they have various functions in the plant, such as physiological regulation, defense against microorganisms, protein storage, carbohydrate transport, and recognition of nitrogen-fixing bacteria of the genus Rhizobium [69]. They can form specific bonds with sugars and enterocytes, modifying their ability to absorb nutrients; they also have an agglutinating action on red blood cells, depending on the type of legume and the type of heat treatment it undergoes [89]. They are sensitive to heat treatment; improperly cooked beans can be toxic to humans, causing nausea, vomiting, diarrhea, and bloating, likely due to incomplete denaturation of the lectin which can withstand moderately high temperatures [89].

Phytic acid (inositol-hexaphosphoric acid) represents the main phosphorous reserve in the plant and has the ability to chelate multivalent metal ions, particularly iron, calcium, and zinc, with which it forms insoluble complexes that are more difficult to digest and therefore less available for intestinal absorption [89]. Oxalates are found in most legumes in the form of potassium or calcium salts and, like phytates, are capable of decreasing the bioavailability of mineral salts, particularly calcium. Food-derived oxalate is also involved in the formation of calcium oxalate kidney stones [89].

The main phenolic compounds found in legumes are tannins, phenolic acids, and flavonoids, and the species that contain the most polyphenols are the dark ones (red bean and black bean) [89]. Tannins have reactive groups that can form stable complexes with proteins and other macromolecules, especially during cooking. They are able to inhibit the activity of proteolytic enzymes, leading to a reduction in protein digestibility; they precipitate salivary proteins, leading to the characteristic astringent taste. They also change the intestinal pH, altering the mucosa and reducing micronutrient absorption. Finally, they are able to form complexes with minerals and trace elements, reducing their bioavailability [89].

Saponins are a group of glucosides known for their property of reducing surface tension and forming stable foams in aqueous solutions. Among legumes, beans are particularly rich in such compounds and may contain various types of saponins. At high concentrations, they impart a bitter and astringent taste to the food, which limits its consumption in human nutrition [69]. Their anti-nutrient effect is due to their haemolytic activity caused by interactions with the cholesterol present in red blood cell membranes; due to their ability to interact and form mixed

micelles with bile acids and cholesterol, they have been studied for their cholesterol-lowering action, but their long-term toxic effects are still unknown [90].

The pyrimidine glycosides present in the cotyledons of fava beans (vicine and convicine) are responsible for favism: a condition in which individuals with congenital glucose-6-phosphate-dehydrogenase deficiency suffer acute haemolytic anaemia, as the protective effect of the enzyme is lost. These glucosides are stable upon cooking. Legumes that contain vicine and convicine (fava beans in primis, but other legumes may also contain small amounts) should be banned from the diets of those subjects with favism [89]. Cyanogenic glycosides, although present in very small quantities in some bean species (especially black lima bean varieties) and chickpeas, can induce respiratory distress if eaten in large quantities, as after enzymatic hydrolysis by an endogenous glucosidase they release hydrogen cyanide and acetone [91]. Lathyrogens are amino acid derivatives with toxicity, present in chickling vetch seeds. They can cause lathyrism: skeletal deformities, muscular rigidity, and paralysis [89].

Most of the antinutritional factors (enzyme inhibitors, phytic acid, polyphenols, and saponins) in the right quantities have been shown to have beneficial properties, which is why it is important not to eliminate them completely from the diet but to keep intake below toxic levels [32].

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