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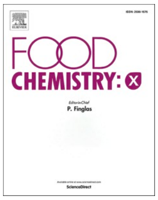

Investigating the physicochemical characteristics and importance of insoluble dietary fiber extracted from legumes: An in-depth study on its biological functions

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ABSTRACT

Legumes are widely appreciated for their abundant reserves of insoluble dietary fiber, which are characterized by their high fiber content and diverse bioactive compounds. Insoluble dietary fiber in leguminous crops is primarily localized in the structural cell walls and outer integument and exhibits strong hydrophilic properties that enable water absorption and volumetric expansion, resulting in increased food bulk and viscosity. This contributes to enhanced satiety and accelerated gastrointestinal transit. The benefits of legume insoluble dietary fiber extend to its notable antioxidant, anti-inflammatory, and anti-cancer properties, as well as its ability to modulate the composition of the intestinal microbiota, promoting the growth of beneficial bacteria while suppressing the proliferation of harmful pathogens, thereby promoting optimal intestinal health. It is highly valued as a valuable thickening agent, stabilizer, and emulsifier, contributing to the texture and stability of a wide range of food products.

1. Introduction

Legumes, which are nutrient-dense foods, play a crucial role in providing humans with essential dietary fiber and other vital nutrients (Tosh & Yada, 2009). Defined as the “pods or fruits” containing seeds or dried grains that exhibit nitrogen fixation in the soil (Kumar & Pandey, 2020). Legumes possess a significant amount of protein, oil, insoluble dietary fiber, starch, and sugar, among other essential components, which contribute to overall well-being (Fujiwara, Hall, & Jenkins, 2016; Hettiaratchi, Ekanayake, Welihinda, & Perera, 2011). To summarize the major constituents (in terms of seed weight percentage) of legume seeds, please refer to Table 1 (Shewry, 2001). The Food and Agriculture Organization of the United Nations (FAO) categorizes pulses into 16 groups, including adzuki beans, parmesan peanuts, broad beans, and others (FAO, 2017). Notably, global pulse production surpasses 92 million tonnes, with Asia accounting for over 42 million tonnes (FAO, 2018). Moreover, apart from its use as a food source, soybean processing generates okara, which finds diverse applications due to its high content of dietary fiber (approximately 50%) and nutrients such as protein (approximately 20%)(Jankowiak, Trifunovic, Boom, & van der Goot, 2014; Redondo-Cuenca, Villanueva-Suárez, & Mateos-Aparicio, 2008; van der Riet, Wight, Cilliers, & Datel, 1989). However, predominantly due to its unpalatability and perishability, a significant portion of okara is either utilized as animal feed or discarded as waste, with only a minor fraction being fully utilized (Ahn et al., 2010; Harthan & Cherney, 2017; Santana et al., 2016). Consequently, the extensive attention of researchers is now drawn towards exploring the comprehensive utilization and high-value potential of bean dregs, to maximize resource utilization within the soybean product industry.

Dietary fiber holds a prominent position among the essential nutrients, ranking seventh, as affirmed by nutritionists (Swallah, Fan, Wang, Yu, & Piao, 2021). Back in 2008, a consolidated definition was established to delineate dietary fiber as a complex carbohydrate polymer comprising three or more monomeric units that are impervious to hydrolysis or absorption by human digestive enzymes (Spiller, Amen, & Kritchevsky, 1975; Stephen et al., 2017). It is noteworthy that dietary fiber can be categorized into two principal types: soluble dietary fiber (SDF) and insoluble dietary fiber (IDF) (Hwang, Charchoghlyan, Lee, & Kim, 2015; Nsor-Atindana, Zhong, & Mothibe, 2012). The former encompasses substances such as pectin, inulin, fructan, β-glucan, and arabinoxylan (Chawla & Patil, 2010), while the latter includes non-starchy polysaccharides that are insoluble in hot water, such as

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Table 1
Main components of legume seeds (seed weight percentage).

Legume	Protein %	Lipid %	Carbohydrates %	Fiber %
Adzuki beans	19.87	0.53	62.9	12.7
Soybean	35.1–42	17.7–21.0	7.7	20
Kidney bean	20.9–27.8	0.9–2.4	41.5	10
Pea	18.3–31	0.6–5.5	45	12
Broad bean	26.1–38	1.1–2.5	37–45.6	7.5–13.1
Lentil	23–32	0.8–2	46	12
Chickpea	15.5–28.2	3.1–7	44.4	9
Mung bean	22.9–23.6	1.2	45	7
Pigeon peas	19.5–22.9	1.3–3.8	44.3	10

cellulose, hemicellulose, and lignin (Jingzhi, Jinhe, & Yuwei, 2011). Insoluble dietary fiber (IDF) resists enzymatic degradation in the digestive system and thus enters the large intestine, where it induces a fermentation process by intestinal microorganisms to produce secondary metabolites (Lamothe et al., 2021). Moreover, IDF enhances intestinal motility, which promotes fecal elimination from the body. IDF derived from diverse sources exhibits distinctive physicochemical properties, including readily available microbial fermentation, cation exchange, water retention capabilities, viscosity, binding capacities, absorption potential, structural expansion faculties, and adsorption functions (Nsor-Atindana et al., 2012). Recent years have witnessed a surge in comprehensive research, unveiling a plethora of biological activities associated with IDF, leading to its widespread application. Numerous studies have conclusively demonstrated the profound role of legume-derived IDF in modulating cardiovascular diseases, diabetes, cancer, and fostering gastrointestinal well-being (McRorie & McKeown, 2017; Nsor-Atindana et al., 2012; Salah, Azab, Ramadan, & Hanora, 2019; Weickert & Pfeiffer, 2018). Consequently, an escalating focus on comprehending the physicochemical attributes and biological functionalities of IDF has materialized.

This comprehensive review seeks to investigate the multifaceted role and profound impact of insoluble dietary fiber (IDF) on human health. It endeavors to diligently examine and elucidate the intricate physiological and biochemical mechanisms underlying the beneficial effects of IDF in legumes. Moreover, this review critically assesses the diverse applications of IDF in modern food processing techniques and underscores the potential for future research investigations in this domain. By shedding light on the physiological relevance and interplay of IDF in legumes, this review not only enhances our understanding of these bioactive compounds but also contributes to the optimization of their utilization and economic value in the context of pulses and their byproducts. Importantly, this scholarly endeavor holds the promise of pioneering novel therapeutic strategies for ameliorating specific human diseases.

2. Research methods

In this paper, information on the structural composition, physicochemical properties, and applications of insoluble dietary fiber (IDF) from legumes in food processing was reviewed through various literature databases and search engines on the Internet, including X-MOL, Google Scholar, PubMed, CNKI, AbleSci, and Scopus. By integrating the obtained information, the bioactive mechanism of legume-insoluble dietary fiber in maintaining human health was analyzed, and the prospects of legume-insoluble dietary fiber in the food industry were discussed.

3. Physical and chemical properties of leguminous dietary fiber

3.1. Compositional analysis of insoluble dietary fiber in legumes

Insoluble dietary fiber (IDF) manifests as a complex polysaccharide system, comprising a rich diversity of components including cellulose, hemicellulose, and lignin (Chawla & Patil, 2010). These constituents serve as the primary building blocks of the cell wall microfibrils, with each compound intricately interwoven within multiple layers to form the robust structure of IDF (Y. Liu, Zhang, Yi, Quan, & Lin, 2020). The crucial constituents of cellulose, hemicellulose, and lignin, forming the essential components within the cellular matrix of legume-derived IDF, underscore their vital structural and functional roles. Notably, variations in monosaccharide composition across different legumes emphasize the distinct nature of IDF, predominantly featuring galactose, arabinose, galacturonic acid, xylose, alongside other constituents. Cellulose, upon complete hydrolysis, yields glucose, whereas hemicellulose, under similar conditions, releases glucose, xylose, mannose, arabinose, and galactose (Mudgil & Barak, 2013). Lignin, on the other hand, consists of guaiac, lilac propane, and hydroxyphenyl propane.

Cellulose, a predominant constituent of plant cell walls, is primarily located within the hemicellulose and lignin matrix (Baky et al., 2022). This structural polysaccharide consists of β-(1,4)-linked ᴅ-glucose units arranged in a linear homopolymeric fashion, providing the framework for higher plant cell walls in the form of crystalline microfibers (Pauly & Keegstra, 2008). The metabolism of cellulose entails a collaborative effort involving three distinct enzymes, namely endoglucanase, exoglucanase, and β-glucanase (Horn, Vaaje-Kolstad, Westereng, & Eijsink, 2012). These enzymatic catalysts facilitate the breakdown of cellulose into readily assimilable monosaccharides, thereby enabling cellulose recycling within the surrounding environment.

Hemicellulose, a polysaccharide ranking second only to cellulose in abundance throughout nature, serves as a non-cellulosic component encompassed within both primary and secondary cell walls (Pauly et al., 2013). While the specific composition of hemicellulose may vary across different growth stages of a given crop, the fundamental structure remains remarkably consistent (G. Cheng et al., 2008). Depending on its origin, hemicellulose can be classified into three primary categories: arabinoxylan (AXs), galactose glucose mannan, and glucuronic acid xylan. In beans, arabinoxylan constitutes the predominant form of hemicellulose. The chemical structure formula of cellulose, hemicellulose, and lignin is shown in Fig. 1 (Ziping, Hong, & Da, 2011). AXs are structurally characterized by the presence of pentose sugars, specifically xylose and arabinose, forming a linear backbone through β-(1,4) glycosidic linkages. Moreover, α-l-arabinofuran monomers predominantly attach to the O-2 or O-3 positions (single substitution), while xylosyl groups can be found branching from both the O-2 and O-3 positions (double substitution) as side chain residues (Gao, Guo, Wang, Zhao, & Wang, 2022). Consequently, a comprehensive structural characterization of hemicellulose necessitates the utilization of an integrated approach. For instance, the hemicellulose content, the number of reducing terminals and branches, as well as the aldehyde acid composition, can be determined via ultraviolet absorption spectroscopy (Ebringerová, Kardosová, Hromádková, Malovíková, & Hríbalová, 2002). Similarly, gas-liquid chromatography enables the identification of specific glycosidic bond types and linkage patterns within the constituent sugars of hemicellulose (J.-Q. Huang et al., 2017).

In stark contrast to the compositional simplicity exhibited by cellulose and hemicellulose, lignin stands as a remarkably intricate macromolecule. Advances in current research suggest that lignin forms a three-dimensional network, characterized by a phenylpropane structure, critically influencing the integrity of plant cell walls. Within these cell walls, lignin fulfills the indispensable role of bridging the gaps between cellulose and hemicellulose constituents (Sun, 2020). Lignin comprises a triad of alcohol monomers: p-coumarol, coniferol, and glucinosol. Due to its dense polymer network and aromatic nature, lignin undergoes depolymerization via oxygen-dependent mechanisms, facilitated by enzymes such as lignin peroxidase (LiP), manganese peroxidase (MnP), multifunctional peroxidase (VP), and dye-decolorizing peroxidase (DyP) peroxidase (de Gonzalo, Colpa, Habib, & Fraaije, 2016). Furthermore, pyrolysis emerges as an alternative strategy for the conversion of lignin (Yupeng, 2022).

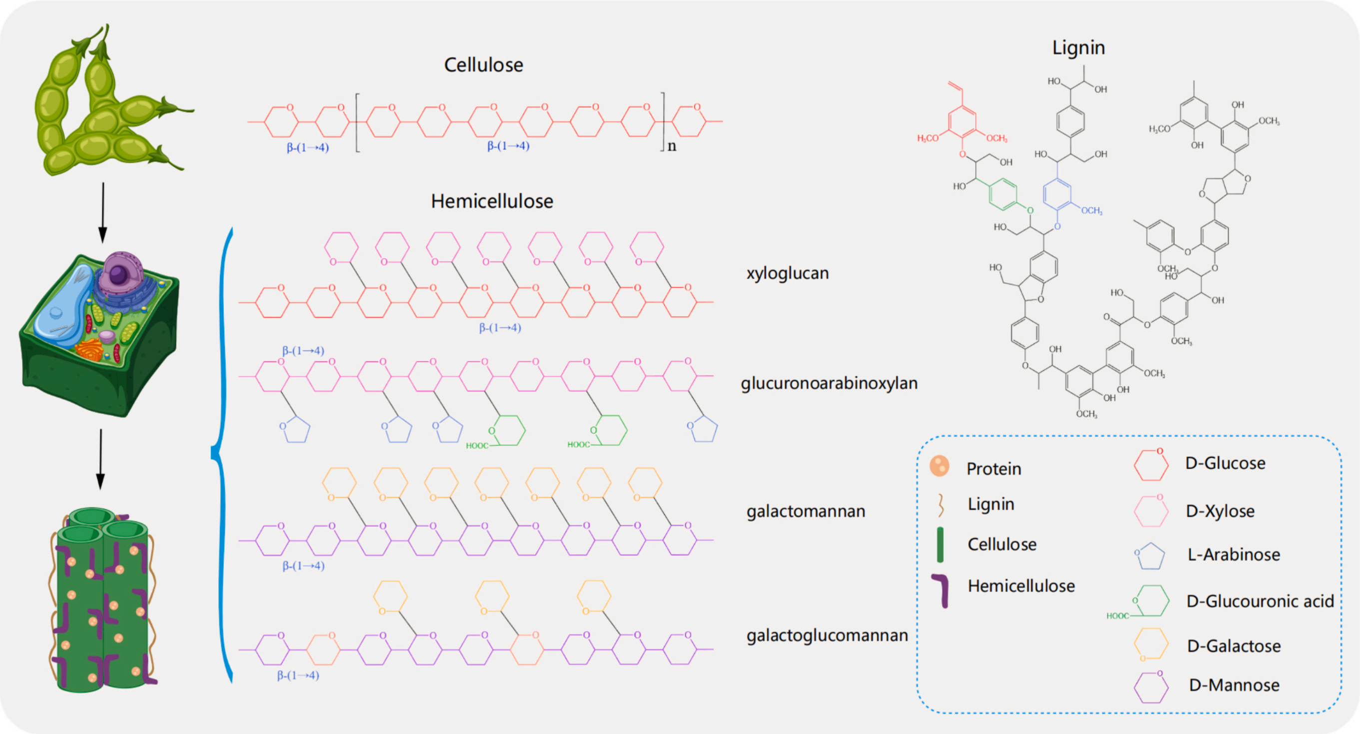

Fig. 1. Cellulose, hemicellulose, and lignin structures in legume dietary fiber.

Within this intricate framework, the monosaccharide composition of high-purity okara insoluble dietary fiber (HPIDF), as analyzed through meticulous acid hydrolysis by Lyu et al. (2021), exhibits a prominent presence of galactose (47.00%), arabinose (22.40%), galacturonic acid (15.80%), xylose (6.40%), rhamnose (3.20%), glucose (2.30%), mannose (1.00%), fucose (1.50%), and glucuronic acid (0.40%). Furthermore, Inmaculada et al. explored the monomer distribution in broad bean pods, establishing glucose (40–45%) as the preponderant monomer, followed by uronic acid (16–24%), arabinose (13–14%), galactose (13–14%), and xylose (8%) (Mateos-Aparicio, Redondo-Cuenca, & Villanueva-Suárez, 2011). Meanwhile, the composition of monomers in pea pods varied significantly, with glucose (42–43%) and xylose (39–41%) attaining the highest proportions, while uronic acid (9%), galactose (4%), and arabinose (2%) constituted smaller fractions. For chickpeas, David et al. (Dalgetty & Baik, 2003) identified arabinose (51.4%), glucose (27.4%), xylose (20.9%), and uronic acid (0.2%) as the primary monosaccharides within IDF, while lentils exhibited arabinose (45.7%), glucose (31.7%), xylose (19.8%), and uronic acid (2.8%) as the predominant monomers. In peas, the main monosaccharides detected in IDF were arabinose (46.3%), glucose (31.3%), xylose (20.8%), and uronic acid (1.7%). These findings serve as pivotal references for comprehending the physicochemical attributes of IDF within legumes and hold substantial implications for its utilization in food processing. Furthermore, these endeavors significantly contribute to an expanded understanding of the compositional intricacies and physiological functions of insoluble dietary fiber present in beans and other plant-based food sources.

3.2. Sources and differences of insoluble dietary fiber

The primary sources of insoluble dietary fiber encompass various categories such as grains, legumes, as well as fruits and vegetables. Cereals fall under the category of monocotyledonous plants, which characteristically exhibit dissimilar cell wall glycopolysaccharide structures and compositions compared to legumes (Awika, Rose, & Simsek, 2018). These distinctions consequently give rise to variations in the dietary fiber content found in cereals versus legumes. In grain cell walls, neutral polysaccharides like cellulose and hemicellulose dominate, whereas legumes have a minimal proportion of pectin or structural proteins (Jarvis, Forsyth, & Duncan, 1988; Vogel, 2008). Whole grains primarily composed of cellulose, arabinoxylan, and mixed-chain beta-glucans (Saulnier, Guillon, & Chateigner-Boutin, 2012). This makes their dietary fiber primarily insoluble. On the contrary, legumes consist of cellulose, xyloglucan, and pectin (Tosh and Yada, 2009). Legumes contain a higher proportion of soluble dietary fiber. Moreover, the content and composition of insoluble dietary fiber can vary slightly among different legume varieties. This variation can be attributed to the specific combinations and levels of cellulose, hemicellulose, and lignin present in each type of legume. These distinctions highlight the importance of considering the specific legume variety when analyzing its dietary fiber content. These variations in polysaccharide composition and characteristics play a crucial role in determining the structural integrity of the cell wall and its susceptibility to disruption by digestive processes such as gastric pH, endogenous enzymes, and microbial action. They also influence the release or retention of other biologically active compounds within the cell matrix and their subsequent location of release in the gastrointestinal tract. Polysaccharides derived from cereal cell walls are more likely to withstand the digestive process and remain relatively intact until reaching the colon, thereby exhibiting greater resistance to microbial degradation (Awika et al., 2018). Zhang et al. conducted a study to investigate the composition of dietary fiber in three types of grains (quinoa, buckwheat, and barley) and two legumes (peas and mung beans). The results revealed that the insoluble dietary fiber in the three cereals had lower lignin content compared to the legumes, with mung beans exhibiting the highest lignin content. Furthermore, quinoa, buckwheat, and barley contained higher levels of cellulose and hemicellulose compared to the legumes (D. Zhang, Wang, Tan, & Zhang, 2020). Insoluble dietary fiber (IDF) in fruits and vegetables has a more diverse monosaccharide composition, including xylose, arabinose, galactose, glucose, mannose, and uronic acid (do Espirito Santo et al., 2020). In contrast, fruits and vegetables tend to have higher levels of soluble dietary fiber compared to legumes. According to a study by Alba et al., the insoluble dietary fiber in blackcurrants displayed lower levels of cellulose and hemicellulose, but higher levels of lignin, compared to green beans and peas (Alba et al., 2018). Correlation analysis demonstrated significant positive associations between pectin, hemicellulose, cellulose contents, and hydration capacity, whereas lignin content showed a significant negative correlation with hydration capacity (Zhang et al., 2020). These findings suggest that the composition of insoluble dietary fiber from different sources contributes to discrepancies in their physicochemical properties. These physicochemical properties influence the health benefits associated with the consumption of dietary fiber. For example, the resistance of cereal-derived fiber to digestion allows it to function as a prebiotic, promoting the growth of beneficial gut bacteria. In contrast, soluble fiber derived from fruits and vegetables can help to regulate blood glucose levels by slowing the absorption of glucose into the bloodstream. Additionally, certain types of dietary fiber can bind to cholesterol, promoting its excretion and reducing the risk of heart disease. Overall, the composition of dietary fiber varies widely depending on the source, and this composition can impact its physicochemical properties, digestive processes, and health benefits. Understanding these differences can help individuals make informed dietary choices and optimize their health outcomes.

3.3. *Basic physical and chemical properties*

Water holding capacity (WHC) is a crucial physicochemical property of Insoluble dietary fiber (IDF) that refers to its ability to retain water, encompassing bound water, hydrodynamic water, and physically trapped water, under external centrifugal gravity (Jacometti et al., 2015). The WHC of IDF is influenced by several factors, including the structure, number, and nature of water-binding sites present in the insoluble dietary fiber (IDF) components. Recent studies have investigated various legumes to determine their WHC (Jacometti et al., 2015). For instance, Lyu and colleagues discovered that soya bean dregs IDF had a remarkable water-holding capacity compared to rice bran IDFs (Lyu et al., 2021; Wen, Niu, Zhang, Zhao, & Xiong, 2016). Similarly, Wang et al. reported that pea IDF exhibited good WHC (Wang, Li, Wang, Liu, & Ni, 2021). Conversely, Diedericks et al. observed that chickpeas had lower IDF water-holding capacity (Diedericks & Jideani, 2015). However, lower WHC might be beneficial in food production, such as when added to bread, which can affect product yield, functional ingredients, and shelf-life (Guillon & Champ, 2000; Rosell, Santos, & Collar, 2008). Additionally, the water-holding properties of legume IDF might also influence human health, with high WHC contributing to colonic defecation. Keskin and Mannuramath et al. examined the water-holding capacity of dietary fiber in six legumes, finding that black beans and lentils displayed the highest WHC, possibly due to their higher content of pectin, cellulose, and hemicellulose (Keskin et al., 2022; Mannuramath & Jamuna, 2012).

Oil holding capacity (OHC) of dietary fiber refers to its capacity to physically or chemically retain significant quantities of oil and prevent its leaching (Elleuch et al., 2010). This property is crucial in minimizing fat loss during cooking and facilitating the removal of excess fat from the body (W. Zhang et al., 2017). Previous studies have indicated that the insoluble dietary fiber present in legumes, such as green beans and peas, exhibits a pronounced OHC, whereas fruits, vegetables, and seaweeds have a lower OHC when compared to legumes (Figuerola, Hurtado, Estévez, Chiffelle, & Asenjo, 2005; Gómez-Ordóñez, Jiménez-Escrig, & Rupérez, 2010). This disparity may arise from the elevated lignin content within the insoluble dietary fiber of green beans and peas. The research conducted by Kumari et al. demonstrates that insoluble dietary fibers derived from pea skin possess a high water-holding capacity (WHC) and a low oil-holding capacity, indicating their potential suitability as a dietary resource for the development of functional food products that address water synergism in formulated foods and act as emulsifiers for high-fat foods (Kumari, Das, & Deka, 2022; K. Wang, Li, et al., 2021). Additionally, Mannuramath et al. discovered that soybean dietary fiber exhibits a higher oil-holding capacity compared to other commonly consumed legumes (Mannuramath and Jamuna, 2012). This phenomenon is likely attributable to the substantial presence of insoluble components (e.g., mucopolysaccharides, lignin, cellulose, and hemicellulose) within soybean dietary fiber, which bolster its ability to bind with fats and oils (S.-C. Huang et al., 2009; Vaz Patto et al., 2015).

The swellability of dietary fiber refers to its ability to increase in size or gelatinize when mixed with water. Insoluble dietary fiber is indigestible and non-absorbable, hence it increases fecal volume and consistency, thereby stimulating intestinal peristalsis, ameliorating constipation, and enhancing intestinal health. Additionally, the ability of insoluble dietary fiber to swell can create a sense of fullness, which ultimately results in a decrease in food intake and can facilitate weight management (Burton-Freeman, Liyanage, Rahman, & Edirisinghe, 2017). Diedericks et al. investigated the swellability of insoluble dietary fiber (IDF) extracted from Bambara peanut flour with varying colors and observed that the swellability of IDF ranged from 6.37 mL/g to 7.72 mL/g (Diedericks and Jideani, 2015. These findings showed that Bambara peanut IDF had a higher swellability in comparison to oat and bamboo fibers, as previously reported by Wang et al. where the values for swellability were 4.98 mL/g and 5.69 mL/g, respectively (N. Wang & Toews, 2011). The IDF from chickpeas had a swellability of 4.28 mL/g, whereas lentil IDF had a swellability of 8.04 mL/g, as reported by Dalgetty et al.(Dalgetty and Baik, 2003). Moreover, Luo et al. established that IDF extracted from soybean dregs had better swelling properties compared to IDF derived from bamboo shoots and rice bran (Luo et al., 2017; Wen et al., 2016). Wang et al. reported the in vivo swelling of pea IDF, which induced satiety and possessed anti-obesity effects in experiments with mice fed with ultramicro-milled modified pea IDF (Wang et al., 2021).

4. Biological functions of leguminous dietary fiber

4.1. *Improves gut health*

The gut microbiota is a diverse assembly of microbial communities that establish distinct ecological niches within a complex ecosystem encompassing bacteria, eukaryotes, fungi, and a select few viruses (Cornejo-Pareja, Muñoz-Garach, Clemente-Postigo, & Tinahones, 2018). As a pivotal component of the human organism, the intestinal microbiota exerts a significant influence on metabolic and energetic processes as well as gut health. An increasing body of research has revealed a close relationship between the composition and abundance of the gut microbiota and several chronic metabolic disorders, most notably, obesity, diabetes, and cardiovascular disease. Indeed, numerous pathological conditions are associated with dysbiosis, reflecting modifications to the composition and/or functioning of the intestinal microbiota. Such dysbiosis can stem from innate genetic factors or can arise from a range of environmental factors, which shape the gut microbiota through direct and indirect impacts. Fig. 2 illustrates the advantageous effects of insoluble dietary fiber derived from legumes on human health. Among the extrinsic factors, including diet, alcohol consumption, exercise, and medication usage, diet has demonstrated the most notable impact on the composition of the gut microbiota (Chi et al., 2018; C. He et al., 2018). The dietary structure exerts a crucial role in shaping the intestinal microbiota. Consequently, a prolonged intake of high-calorie diets disrupts the equilibrium of the gut microbiota, diminishing its diversity and abundance, thus fostering the development of dyslipidemia, obesity, and associated metabolic disturbances (N. Cheng, Chen, Liu, Zhao, & Cao, 2019). Conversely, adopting a healthy dietary regimen, such as augmenting the consumption of dietary fiber and prebiotics, exerts a significant positive influence on the richness and diversity of intestinal microorganisms, ultimately preserving the homeostasis of the intestinal microecosystem. Table 2 succinctly presents a comprehensive overview of the biological functionalities associated with leguminous dietary fiber.

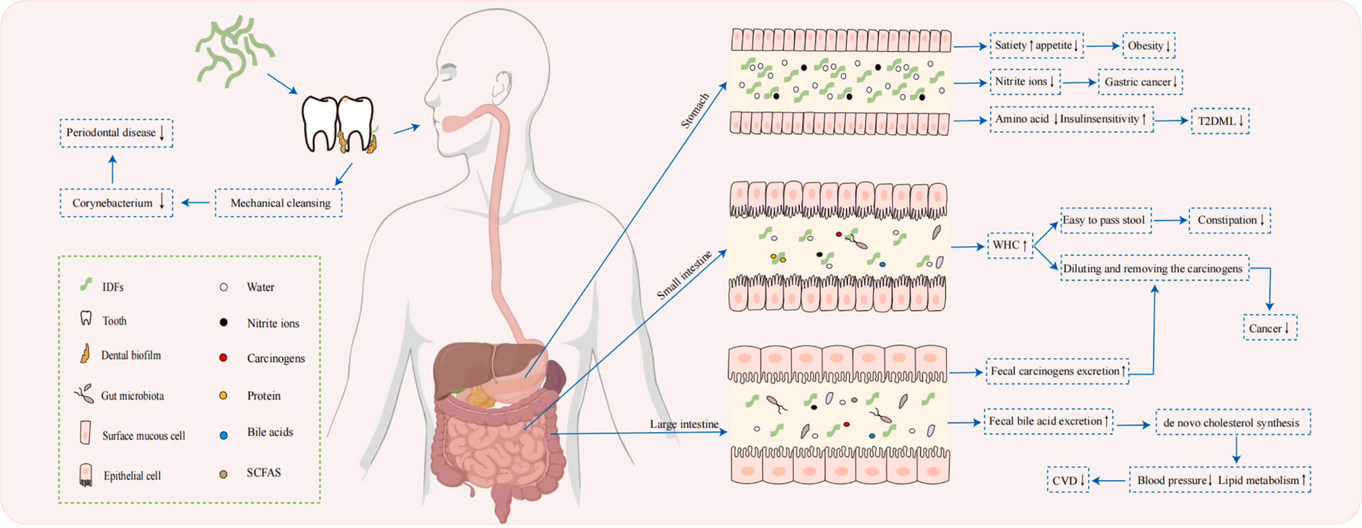

Fig. 2. Benefits of legume-insoluble dietary fiber on human health.

Insoluble dietary fiber (IDF) possesses commendable physiological attributes, namely the facilitation of intestinal peristalsis, enhancement of intestinal flora structure, and adsorption of detrimental substances (Feng et al., 2022). The correlation between insoluble dietary fiber and intestinal well-being is predominantly manifested across two key aspects (Merenkova, Zinina, Stuart, Okuskhanova, & Androsova, 2020): Firstly, insoluble dietary fiber exerts influence on the flora's structure, thereby inducing alterations in secondary metabolites that impact the intestinal environment. Secondly, insoluble dietary fiber can modulate fecal composition, consequently exerting an indirect influence on intestinal properties and overall metabolic processes. Studies have shown that dietary fiber contributes to different microbial changes and is associated with reduced weight gain and improved blood sugar and lipid metabolism (Li, Guo, Ji, & Zhang, 2016). An imbalance within the gut microbiota, an integral component of both the digestive and immune systems, can compromise the body's resistance to certain diseases. Hence, the maintenance of an adequate dietary fiber intake is imperative for sustaining gut health (Morozov, Isakov, & Konovalova, 2018). Wang et al. (2021) demonstrated that the consumption of soybean insoluble dietary fiber (SIDF) elevates the relative abundance of beneficial bacteria such as Lactobacillus and Leptospirosis while reducing the relative abundance of harmful bacteria such as Helicobacter Leptospiaceae and Bacteroides. This successful modulation of microbiota composition increases the production of short-chain fatty acids (SCFAs), resulting in augmented secretion of satiety hormones and presenting the potential for obesity intervention. Bacteriodes immitis facilitates the process of intestinal mucosal angiogenesis, thereby preserving the equilibrium of the intestinal microecosystem, fostering the maturation of the immune system, and enhancing the host's immune response (Hooper, 2004; Sears, 2006). Moreover, Lactobacilli, through the production of bile acid hydrolase, exert a notable influence on the metabolism of blood cholesterol by the liver, thereby impacting the dynamics of the bile acid cycle (Jernberg, Löfmark, Edlund, & Jansson, 2010). Furthermore, Liu et al. (2021a) illustrated that other physiological benefits of insoluble dietary fiber (IDF) encompass improved bowel movements, fecal consistency, and increased frequency of bowel movements.

4.2. Prevent obesity

The significance of insoluble dietary fiber in the prevention of obesity can be appreciated through three primary facets: Firstly, insoluble dietary fiber demonstrates remarkable oil adsorption capabilities, thereby impeding excessive fat intake by the body and facilitating its elimination alongside the fiber (Lan, Chen, Chen, & Tian, 2012); Secondly, insoluble dietary fiber possesses excellent swelling properties, which leads to increased satiety and subsequently reduces food consumption (Cui et al., 2019); Thirdly, by influencing the composition of the intestinal flora, insoluble dietary fiber can induce alterations in the body's lipid metabolism process (Li et al., 2016). Disorders in lipid metabolism play a pivotal role in the development of obesity. The regulation of lipid metabolism is intricate and involves various signaling pathways, including those governing fatty acids, triglyceride (TG) synthesis, and fatty acid oxidation (Brownlee, 2011). Han et al. found that compared with the high-fat diet group of rats, chickpea IDF (CDF) can significantly reduce rat body weight by 14.54% and 29.34% in the third and fifth weeks, respectively, revealing that CDF has an anti obesity effect. The mechanism of action may be achieved by regulating lipid metabolism and gut microbiota structure. CDF significantly reduces TG and LDL-C in rats, with a decrease of 51.51% and 40.45% compared to the control group, respectively, and can increase HDL-C levels. The gut of rats consuming CDF exhibits the highest bacterial diversity and optimal stability. The relative abundance of Actinobacteria increases, leading to an increase in intestinal SCFA levels. The content of propionic acid, acetic acid, and butyric acid also increases, reducing the expression level of inflammatory factors and thereby affecting the expression of fasting induced adipokines.(Han et al., 2021a). Furthermore, The experiment conducted by Wang et al. on mice also yielded similar results (Wang, Yu, et al., 2021). The liver is an important part of fatty acid metabolism. Huang et al. reported that fatty acids are produced in a series of enzymatic processes and can be oxidized and metabolized into carbon dioxide and water with sufficient oxygen supply. This process is accompanied by a tremendous release of energy. β-oxidation is the main type of fatty acid oxidation (X. Huang, Zhou, Sun, & Wang, 2022). Very long chain fatty acids enter the peroxisome to form shorter acyl coenzymes, which then undergo beta-oxidation in the mitochondria to acetyl-coA, and finally enter the tricarboxylic acid cycle to produce carbon dioxide and water (Mannaerts, Van Veldhoven, Van Broekhoven, Vandebroek, & Debeer, 1982; Yao et al., 2022). By feeding HPSIDF to mice, Zhang et al. found that Intake HPSIDF significantly reduces the high fat diet in mice's liver acyl coenzyme A oxidase, malonyl coa, and acetyl coenzyme A carboxylase level, It promotes the oxidation of medium and long chain fatty acids in liver mitochondria, thus promoting the overall fatty acid oxidation (J. Zhang et al., 2023).

4.3. Intervene in glycolipid metabolism

IDF has a good glucose adsorption capacity (GAC), and this ability might be related to the porosity, surface area, and hydration properties

Table 2
Biological functions of leguminous dietary fiber.

Features of IDF	Mechanism		References
Hypoglycemic	Good glucose adsorption capacity	Enhance capillary action and promote adsorption	Niu (Niu et al., 2022)
		Polar and non-polar functional groups improve the interaction between glucose molecules	Elleuch (Elleuch et al., 2010)
		Good water holding and expansion capacity	Zhanm (Zhanmei et al., 2022)
	Inhibition α-Amylase and α-Glucosidase activity	IDF network structure reduces enzyme accessibility to starch	Tan (Tan et al., 2022)
		Competitive and non competitive inhibition of enzymes	Abdel (Abdel-Haleem, 2019)
		Polyphenols in IDF affect enzyme activity	Gartaul (Gartaula et al., 2017)
	Fermentation produces SCFAS	Regulating appetite and affecting insulin secretion	Hou (Hou et al., 2021)
Preventing malignant diseases	Strong adsorption capacity	Adsorption of heavy metals, benzopyrene, nitrite, and acrylamide	Wang (H. Wang et al., 2016)
Preventing cardiovascular diseases	Good cholesterol adsorption capacity	Reduce low-density lipoprotein cholesterol in the blood	Anders (Anderson, Smith, & Washnock, 2018)
Promoting intestinal health	Fermentation of gut microbiota	Functional polysaccharides that produce probiotic effects	Li (Li et al., 2016)
	Adjusting microbial community structure	Increase the relative abundance of beneficial bacteria and reduce the relative abundance of harmful bacteria	Wang (Wang, Yu, et al., 2021)
	Regulating fecal composition	Fecal consistency and increased frequency of bowel movements	Liu (X. Liu et al., 2021b)
Prevent Obesity	Good oil holding capacity	Promote fat to be excreted from the body along with fibers	Cui (Cui et al., 2019)
	Good expansion ability	Increase satiety, thereby reducing food consumption	Huang (X. Huang et al., 2022)
	Regulating lipid metabolism	Reduce total cholesterol, triglycerides, and low-density lipoprotein cholesterol levels, while increasing high-density lipoprotein cholesterol levels	Han (Han et al., 2021b)

of IDF (Yu, Bei, Zhao, Li, & Cheng, 2018). Postprandial blood sugar rapidly increases. The consumed food is digested and hydrolyzed in the small intestine to produce glucose molecules, which are then actively transported by SGLT-1 in the intestinal mucosa and passively adsorbed by cis concentration gradients and paracellular permeation at high glucose concentrations, leading to an increase in blood sugar levels (Moore, Coate, Winnick, An, & Cherrington, 2012). The intervention mechanism of insoluble dietary fiber in glucose metabolism encompasses three primary aspects: Firstly, the porous structure of IDF can enhance its capillary effect and promote its affinity adsorption for glucose molecules. In addition, this porous structure helps to increase the contact area between IDF and glucose molecules, allowing glucose molecules to remain on the fibers, thereby inhibiting glucose diffusion (Niu et al., 2022). The polysaccharide chains of IDF expose more polar and non-polar groups, including free hydroxyl, ether, phenolic, and carboxyl groups, which improve the interaction between IDF and glucose molecules, leading to high glucose adsorption and directly reduce glucose adsorption in the intestine, lowering blood sugar levels (Elleuch et al., 2010). Thirdly, the hydration performance of IDF mainly refers to its water holding capacity (WHC) and swelling capacity (SC). When the WHC is high, hydrophilic glucose molecules are more likely to enter the fibers, leading to high glucose adsorption (Zhanmei et al., 2022). The WHC and SC of IDF are related to the functional groups present in IDF, including hydrated hydroxyl, carboxyl, and uronic acid groups. These groups can adsorb water molecules through capillary action and hydrogen bonds, resulting in a high WHC and SC for regulating blood sugar (Daou & Zhang, 2013). Additionally, high WHC and SC increase the feeling of satiety and shorten the feces retention time in the intestine, thereby decreasing food intake and reducing the contact of glucose molecules with the intestinal wall to decrease blood sugar levels and synergize with the GAC of IDF to achieve better glycemic regulation.

Starch, among the most important carbohydrate sources, is the major dietary energy source for humans. After ingesting food, starch is hydrolyzed into glucose molecules by α-amylase and α-glucosidase, thereby increasing postprandial blood sugar levels (L. Cheng et al., 2017). α-Amylase and α-glucosidase are the members of the glycosidase family. Therefore, inhibition of α-amylase and α-glucosidase reduces postprandial blood sugar levels, which is vital for preventing type 2 diabetes (Xiaoxiao, Yuxiang, Zhengyu, & Birte, 2021). Prior research has suggested that insoluble dietary fiber (IDF) possesses the capacity to bind with starch granule surfaces, impeding the interaction between α-amylase enzymes and starch granules, thereby inhibiting α-amylase activity (α-AAIRs). This mechanism contributes to the modulation of postprandial blood glucose levels (Dhital, Gidley, & Warren, 2015; Ou, Kwok, Li, & Fu, 2001). The inhibition of α-amylase by insoluble dietary fiber consists of three main aspects. First, the adsorption of α-amylase and α-glucosidase molecules by the IDF network structure reduces their starch accessibility. IDF with a porous structure can directly entrap α-amylase and α-glucosidase molecules in the same way as glucose molecules that are captured to reduce the starch accessibility of enzymes, and the large surface area of IDF can hinder the binding of enzymes to starch (Tan, Macia, & Mackay, 2022). Second, mixed-type (competitive and non-competitive) inhibition of enzymes by IDF. IDF has a mixed-type inhibitory effect on enzymes, which means that IDF binds to enzymes regardless of whether the enzymes are bound to the substrate (T. He et al., 2023). Third, IDF-bound polyphenols inhibit the activity of α-amylase and α-glucosidase (Gartaula, Dhital, Pleming, & Gidley, 2017). The binding of polyphenols in mung bean peel IDF α-amylase and α- glucosidase inhibitory activity>90%(Zheng et al., 2020).

IDF, as nutrient sources, are fermented by the gut bacteria in the colon to produce SCFAs, mainly including acetate, propionate, and butyric acid, and thus regulate blood sugar. The SCFAs produced regulate appetite, influence insulin secretion, and control blood glucose levels. SCFAs can activate two members of the G-protein-coupled receptors (GPCRs), namely GPR41 (FFA2) and GPR43 (FFA3), to excite L-cells, a type of intestinal endocrine cells scattered throughout the gastrointestinal tract. These L-cells secrete glucagon-like peptide-1 (GLP-1) and Peptide YY (PYY). GLP-1 promotes insulin secretion by pancreatic β cells, enhances the proliferation of these cells, inhibits their apoptosis, and improves insulin sensitivity. PYY reaches the brain and decreases a person's appetite to reduce food consumption, thereby achieving lower blood sugar levels (Hou, Yang, Sun, Jing, & Deng, 2021).

4.4. Prevention of cardiovascular disease

The main risk factors of atherosclerotic cardiovascular disease are high levels of low density lipoprotein cholesterol (LDL-C) in the blood and postprandial hyperglycemia (Fan, Song, Wang, Hui, & Zhang, 2012; Jia, Lorenz, & Ballantyne, 2019; Mirrahimi et al., 2013). Statins are effective drugs for treating cardiovascular diseases, but they are expensive and harmful to the body when taken in large quantities. Due to their good ability to regulate lipid metabolism and lower blood sugar, IDF is expected to become a substitute for this drug, opening up new avenues for the treatment of cardiovascular diseases (Soliman, 2019). Including wheat products like bread in the diet introduces starch that is rapidly digested and absorbed, leading to hyperglycemic and insulinemic reactions. However, incorporating insoluble dietary fiber can counteract this by reducing starch content and inhibiting its absorption, thereby lowering the risk of cardiovascular disease (Fardet, Leenhardt, Lioger, Scalbert, & Rémésy, 2006; Juntunen et al., 2002). Prominent researchers such as Anderson and colleagues have highlighted the cardiovascular and kidney health benefits of soybeans, primarily attributed to their abundant dietary fiber components, which aid in removing excess cholesterol (Anderson, Smith, & Washnock, 1999). Matthan et al.'s study further supports this notion, emphasizing the positive impact of soybean's high dietary fiber content on cardiovascular protection (Matthan et al., 2007). Asif et al. specifically underscores the role of soy protein and dietary fiber in preventing cardiovascular disease by improving glucose metabolism (Asif & Acharya, 2013). Additionally, a 2019 report by Camargo et al. emphasizes that a diet high in dietary fiber, such as soybeans, can effectively reduce the risk of diabetes and cardiovascular disease (de Camargo et al., 2019). Although research directly examining the effects of legume-derived dietary fiber on cardiovascular disease remains limited, related studies have demonstrated that the combination of dietary fiber and natural antioxidants can significantly reduce blood pressure and blood lipid levels while providing overall body protection (Jiménez et al., 2008).

4.5. Prevention of cancer and malignant diseases

The inclusion of insoluble dietary fiber derived from beans has been found to possess significant preventive effects against a wide array of cancers. These findings were corroborated by the study performed by Herman C et al. (Adlercreutz et al., 1995), which revealed that estrogens present in soybeans exerted an intervention effect on the treatment of breast cancer. Additionally, Swallah et al. (2021) provided evidence indicating that okara dietary fiber could modulate the intestinal environment, thereby influencing liver and kidney function in the body. The anti-cancer and anti-malignant disease properties of insoluble dietary fiber can be attributed to its robust adsorption capacity towards various harmful substances, such as heavy metals, benzopyrene, nitrite, and acrylamide (Luo et al., 2017; H. Wang, Huang, Tu, Ruan, & Lin, 2016). In a study led by Xu et al. (Xiqi, 2021), soybean IDF was subjected to modification using H_2O_2, resulting in an increased number of hydroxyl and carboxyl functional groups, as well as a disrupted crystal structure and enhanced porous characteristics. Consequently, the adsorption capacity of modified soybean IDF on Pb^{2+} in aqueous solutions was significantly augmented. Animal experiments evaluating the protective effects of modified soybean IDF against lead-induced liver and kidney damage demonstrated that the treatment effectively alleviated organ swelling caused by Pb^{2+}. Furthermore, insoluble dietary fiber possesses noteworthy immunomodulatory properties, including the stimulation of immune cells and substantial reduction of inflammatory markers (Vos, M'Rabet, Stahl, Boehm, & Garssen, 2007). Wang et al. (Jinyu, Sainan, & Jiahong, 2022) conducted a study where okara IDF was modified using hydrochloric acid, resulting in a marked improvement in the adsorption and removal rate of NO^{-2}.

5. Application of legume insoluble dietary fiber in food processing

The industrial processing of pulses yields a substantial amount of by-products, estimated at approximately 400,000 t per year, primarily destined for animal feed. However, owing to the distinctive chemical, functional, and nutritional composition of these industrial by-products, there is an increasing emphasis on exploring their potential for high-value utilization (Petkowicz, Vriesmann, & Williams, 2017; Rodríguez, Jiménez, Fernández-Bolaños, Guillén, & Heredia, 2006). Traditionally, insoluble dietary fiber supplements have been incorporated into various baked goods, including biscuits and cereals. Nevertheless, research on the integration of fiber content in snacks, beverages, spices, imitation cheeses, sauces, frozen foods, canned meats, meat substitutes, and other food products has experienced steady growth in recent years (McKee & Latner, 2000).

In recent years, there has been a growing interest among food researchers and industry professionals in utilizing okara as a supplementary dietary fiber in various food products, such as beverages, vegetable pastes, rice flour, biscuits, and beef patties (Guimarães et al., 2018; Kang, Bae, & Lee, 2018; Turhan, Temiz, & Sagir, 2009; S. Wang et al., 2015). Notably, okara is incorporated into protein gel foods such as tofu, surimi, and sausage due to its distinct gel properties (Chang et al., 2014; Ullah et al., 2019; Yin et al., 2019). Protein gelation involves the aggregation of unfolded proteins, resulting in the formation of a three-dimensional network that entraps water and other additives (Lanier, Carvajal, & Yongsawatdigul, 2005). Ullah et al. (2019) conducted a study wherein nano-okara fiber (NDF, 370 nm) and micron-okara fiber (MDF, 110 μm) were added to soy milk at different volume ratios during tofu production. The researchers observed that the addition of okara insoluble dietary fiber (IDF) led to a nearly linear increase in the total dietary fiber content of tofu gel, particularly with the concentration of Okara IDF (110 μm), reaching a maximum value of 37.91 g/100 g dry sample when 40% IDF was incorporated. However, analysis of the tofu gel's structural profile (TPA parameters) demonstrated a continued decline with an increasing concentration of okara IDF. This decline primarily stemmed from the disruption of the tofu gel network caused by the coarse-grained IDF particles. As the quantity of added okara increased, the tofu gel's hardness progressively decreased. Furthermore, the inclusion of NDF was found to reduce the hydrophobic interaction and hydrogen bond content of the tofu gel, which had subsequent effects on the secondary structure of soy protein. In contrast, Chang et al. (2014) observed that the addition of okara notably enhanced the hardness, chewiness, and breaking power of pork gel (Chang et al., 2014). This improvement was attributed to okara's water-absorbing properties and its role as a filler within the gel matrix. Another study by Niño-Medina et al. (2019) investigated the incorporation of insoluble and soluble dietary fibers extracted from soybean and chickpea shells into bread. The resulting dough, weighing 40 $\pm$ 0.5 g, was fermented at 40 °C for 12 min and subsequently baked at 170 °C for 15 min. The researchers discovered that bread fortified with dietary fiber exhibited reduced weight loss rates and hardness throughout the storage period. These effects were primarily attributed to the water-holding capacity of the insoluble dietary fiber, while minimal changes were observed in other physical properties such as color. Xiangli, Xuzhi, and Guoguo (2021) conducted a study where soybean insoluble dietary fiber ultrafine powder was incorporated into smoked sausages. The findings revealed that the optimal inclusion of soybean insoluble dietary fiber enhanced the sausages' water-holding capacity, cooking yield, elasticity, and hardness. As a result, this not only reduced the costs associated with the production of sausages but also increased their nutritional value while imparting a distinctive flavor and color. However, the addition of insoluble soy shell fiber to meat products displayed a decrease in color stability and lipid oxidation, thereby further highlighting the potential application of insoluble dietary fiber in the food industry (Kim, Miller, Lee, & Kim, 2016). Fava bean pods, an abundant source of food-grade materials rich in fiber and phytochemicals, are currently underutilized as a secondary product. Qianqian Ni et al. (2020) investigated the incorporation of insoluble dietary fiber from broad bean pods into bread. The experimental outcomes depicted in Fig. 3 indicate that the addition of broad bean pod dietary fiber beyond a concentration of 11% resulted in significantly darker breadcrumb surfaces, diminished porous structure, and considerable alterations in physical and chemical properties. For instance, the specific volume of bread decreased, signifying a decline in gas retention, while an increase in bread density and a decrease in weight loss were observed. Similar findings were reported in a study by Belghith et al. (Belghith Fendri et al., 2016), emphasizing the potential of insoluble dietary fiber from broad bean pods in enhancing dough development and improving bread texture. Camino M et al. (Mancebo, Rodríguez, Martínez, & Gómez, 2017) incorporated insoluble dietary fiber from peas into biscuits. The study found that the addition of pea-insoluble dietary fiber augmented the water-holding capacity (WHC) and water adhesion (WBC) of the biscuits. Furthermore, it led to a decrease in the final width and spreading coefficient of the biscuits, along with increased hardness. Sosulski et al. (Sosulski & Wu, 1988) supplemented bread with insoluble dietary fiber extracted from pea pods. Their research indicated that the bread's texture and grain received the highest sensory evaluation scores when the concentration of pea pod insoluble dietary fiber reached 10%. In a separate study, Yi Shengkui et al. (Shengkui, 2022) introduced modified okara insoluble dietary fiber into a biscuit recipe for 3D-printed cookies. These cookies exhibited superior fidelity compared to those without insoluble dietary fiber. Additionally, the incorporation of insoluble dietary fiber resulted in reduced moisture content,

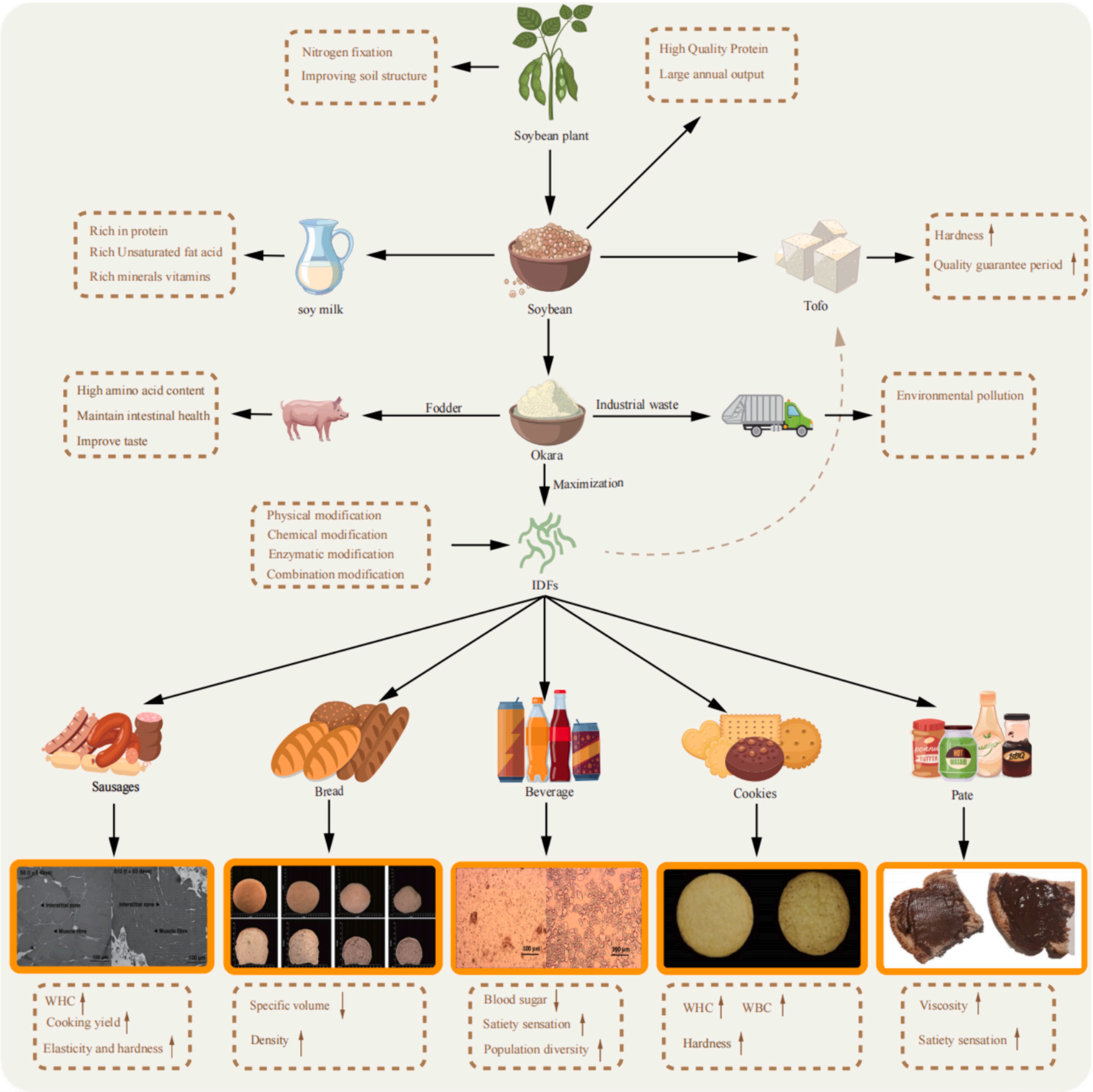

Fig. 3. Application of pulses in food processing

carbohydrate content, and fat content, thereby extending the cookies' shelf life. These improvements make the cookies more suitable for individuals struggling with obesity. Furthermore, Ling Sen et al. (Sen, Chaoxu, & Kai, 2019) proposed the addition of insoluble dietary fiber to milk powder to create a functional milk powder with hypoglycemic effects. This innovation holds the potential to assist diabetics in effectively supplementing their nutritional needs. Overall, these studies demonstrate the valuable role of insoluble dietary fiber from various sources in enhancing the properties and functionality of different food products, yielding economic, nutritional, and sensory benefits.

6. Outlook for the future

IDF, short for insoluble dietary fiber, is a complex polysaccharide that is abundantly present in various leguminous plants, including soybeans, green beans, mung beans, and root and stem parts enriched with lignin. Comprising cellulose, hemicellulose, lignin, and other indigestible components, IDF eludes the hydrolysis process initiated by digestive enzymes within the small intestine, thereby bypassing absorption. Instead, it traverses the gastrointestinal tract and reaches the large intestine, where it substantiates the nourishment required for the fermentation and metabolic activities of gut microorganisms. IDF manifests numerous advantageous effects on human health, encompassing the augmentation of stool bulk and the facilitation of regular bowel movements, as well as the reduction of blood lipid and cholesterol levels. Furthermore, IDF exerts influence on insulin secretion and imparts a decelerating effect on postprandial blood glucose elevation, thus mitigating the risk of developing ailments such as metabolic syndrome and diabetes.

Due to the ubiquitous occurrence of IDF in legumes and various botanical comestibles, the scientific community has initiated efforts towards harnessing its beneficial attributes in the realm of food processing. In this context, IDF has emerged as a frequently employed ingredient, finding utility as a versatile thickening agent, gelling agent, and stabilizer in a range of culinary applications. Remarkably, IDF possesses distinctive properties of mixed gelatinization, thereby tailoring its effects to perfectly suit the specific culinary requirements, including taste and texture enhancements. Furthermore, IDF exhibits hydrophilic properties, rendering it invaluable in food systems wherein moisture retention and structural integrity preservation are crucial considerations. As an illustrative example, IDF finds utility in cereal-based products by lending them the capacity to maintain their shape during processing and subsequent storage. Similarly, in the case of processed meat products like sausages, IDF plays a vital role in water retention, thereby fueling their overall succulence and visual appeal.

The advancement of knowledge in the realm of IDF necessitates further exploration into its distinct functions and operational methodologies as an invaluable and versatile functional food additive across diverse practical implementations. Correspondingly, increased emphasis is being placed on fundamental research concerning IDF, encompassing intricate examinations of its physicochemical properties, crystallization behavior, and establishment of comprehensive mathematical models to elucidate its complex characteristics. Concurrently, sustainable practices must be given due consideration in IDF generation and extraction processes. Specifically, the utilization of diverse leguminous sources and optimization of preparation techniques hold promise in reducing resource dependency and enhancing overall economic efficiency. Through these comprehensive investigations, the ongoing quest to propel IDF's efficacy as a prominent food ingredient gains momentum, thus fostering its propitious integration within the realm of health-related applications.

7. Conclusion

Soybean IDF, characterized by its water-insolubility, comprises a polymer of carbohydrate monomeric units that exhibits remarkable resistance to the enzymatic breakdown within the human small intestine, ultimately culminating in its interaction with the microorganisms dwelling in the intestinal tract, instigating a cascade of beneficial fermentative processes. The wide array of health advantages associated with IDF encompasses the cultivation of a diverse and thriving gut microbiota, bolstered insulin sensitivity, mitigation of obesity and cardiovascular disease risk, potential protection against select cancers, promotion of augmented stool volume and regular bowel movements, and regulation of blood sugar levels. To leverage the myriad benefits of IDF, multiple processing techniques are employed to enhance its physicochemical properties, thus facilitating its integration into the realm of functional food applications. The morphology, structure, and surface characteristics of insoluble dietary fiber emerge as crucial determinants governing its functionality and breadth of application. A comprehensive understanding of these features not only facilitates a better grasp of the immense potential IDF holds within the food industry and medical domains but also serves as a theoretical foundation, paving the way for future research and development endeavors.

Informed consent

Not applicable. Ethical guidelines. Ethics approval was not required for this research.

CRediT authorship contribution statement

Tong Liu: Writing – original draft. **Xinyu Zhen:** Writing – original draft. **Hongyu Lei:** Data curation. **Junbo Li:** Conceptualization. **Yue Wang:** Data curation. **Dongxia Gou:** Writing – review & editing. **Jun Zhao:** Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Data availability

No data was used for the research described in the article.

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