European Food Research and Technology (2026) 252:79
https://doi.org/10.1007/s00217-025-05011-6

REVIEW ARTICLE

Extraction, modification, and application of dietary fibre powders in foods: a review

Ertan Ermis[1] · **Chi-Ching Lee**[1] · **Ismail Hakki Tekiner**[2]

Received: 23 July 2025 / Revised: 14 October 2025 / Accepted: 6 December 2025 / Published online: 21 January 2026

Abstract

Dietary fibres (DFs) have gained significant attention in the food industry due to their functional and nutritional benefits. They are mostly produced in powder form from sources such as fruits, vegetables, and grains. Different production methods can be used for the valorization of dietary fibre-rich food matrices, enabling the development of functional powders with extended shelf life and health-promoting properties. They are rich in soluble and insoluble fibres and their use in food formulations provides several advantages, including improved texture, increased shelf life, and enhanced nutritional value. Recent meta-analyses confirm that soluble fibres improve glycaemic control and lipid profiles, while insoluble fibres primarily contribute to bowel regularity and stool bulking. This review compiles and critically analyzes recent literature retrieved primarily from the Web of Science database (2010–2024), focusing on the sources, extraction and modification methods, powder properties, and functional applications of dietary fibre powders in food systems. Emphasis is placed on the structure–function relationships of DF powders and how different processing methods influence their techno-functional properties, bioactivity, and product quality.

Keywords Dietary fibre · Structure–function relationship · Functional food powders · Bioactive retention

Introduction

Dietary fibre (DF) is defined as carbohydrate polymers and associated plant substances that are resistant to digestion and absorption in the human small intestine, with complete or partial fermentation occurring in the large intestine [1]. The Institute of Medicine recommends a daily DF intake ranging from 19 to 38 g, depending on age and sex, to support optimal gastrointestinal function, whereas the European Food Safety Authority (EFSA) - an independent agency of the European Union, responsible for providing scientific advice on food-related risks - advises a minimum intake of 25 g/day in adults to maintain normal bowel function and overall health [2]. DF falls into two main categories: soluble and insoluble fibres. While pectin, gums, and mucilage become gummy in water, cellulose, hemicellulose, and lignin are insoluble in it. Due to their numerous health advantages, DFs are valuable ingredients with a growing market demand. Additionally, there has been a recent push to identify new sources of DFs that can be utilized in the food sector [3].

By incorporating DF powders into food formulations such as bakery, drinks, beverages and meat products, manufacturers can enhance the nutritional profile of their products and provide consumers with a convenient way to increase their fibre intake [4]. They are typically derived from plant sources such as fruits, vegetables, grains, and legumes, which are rich in fibre content [3]. DFs are essential for promoting proper digestion, maintaining bowel regularity, and supporting overall gut health [5]. Systematic reviews demonstrate that soluble fibres, such as β-glucans and psyllium, significantly lower LDL cholesterol and postprandial glycaemia, whereas insoluble fibres primarily enhance laxation and stool bulk [6]. In addition, DFs, particularly soluble fibers, have been shown to possess detoxifying properties by binding to heavy metals and toxic substances in the

---

✉ Ertan Ermis
ertan.ermis@gmail.com

[1] Department of Food Engineering, Faculty of Engineering and Natural Sciences, Istanbul Sabahattin Zaim University, Istanbul, Turkey

[2] Department of Nutrition and Dietetics, Faculty of Health Sciences, Istanbul Sabahattin Zaim University, Istanbul, Turkey

gastrointestinal tract, reducing the toxicity of heavy metals [7]. Furthermore, DF powders can improve the texture and shelf life of food products, making them more appealing to consumers. However, if the content is too high, their impact often is evaluated not favorable. In summary, DF powders have a wide range of potential uses in food formulations due to their versatility and numerous health benefits [6].

There are various types of DF powders available for use in food formulations. These include soluble fibre powders, insoluble fibre powders, and resistant starch powders. Soluble fibre powders, such as psyllium husk powder and inulin, dissolve in water to form a gel-like substance. This gel-like substance helps to slow down digestion, regulate blood sugar levels, and lower cholesterol levels [8]. Insoluble fibre powders, such as wheat bran and cellulose, do not dissolve in water but add bulk to the stool, promoting regular bowel movements and preventing constipation [9]. Resistant starch powders, such as green banana or potato starch, are not digested in the small intestine and instead fermented in the colon, providing prebiotic benefits by promoting the growth of beneficial bacteria in the gut [10]. Apart from their role in enhancing nutritional value and improving consumer satisfaction, DF powders also offer various functional benefits in food formulations. These functional benefits include improving texture, moisture retention, and stability of food products. Additionally, DF powders can act as thickeners, stabilizers, and emulsifiers in food formulations. They can also contribute to the sensory properties of food, such as mouthfeel and flavor [11].

Despite the growing number of studies on dietary fibre extraction and modification (Fig. 1), existing reviews have predominantly treated these aspects in isolation and have seldom addressed their integration with powder production and application in complex food systems. In particular, limited attention has been given to the powder characteristics of dietary fibres such as particle morphology, flowability, hydration capacity, and bulk density, which strongly influence their behaviour during food processing and formulation. Therefore, this review aims to bridge that gap by consolidating current knowledge on the extraction, powder production, modification, physicochemical characterisation, and functional applications of DF powders derived from diverse plant sources. This approach provided a thorough overview of the current knowledge on dietary fibre powders, their sources, extraction methods, functional properties, and applications in food products. For this review, the selection of scientific literature was carried out through a systematic search of Web of Science database. The search focused on publications from the last fourteen years (2010–2024). Combinations of keywords were used, such as: 'Dietary fibre', 'Soluble dietary fibre', 'Insoluble dietary fibre', 'Functional fibre', 'Dietary fibre powder', 'Fibre powder production', 'Fibre extraction', 'Fibre modification', 'Fibre-enriched

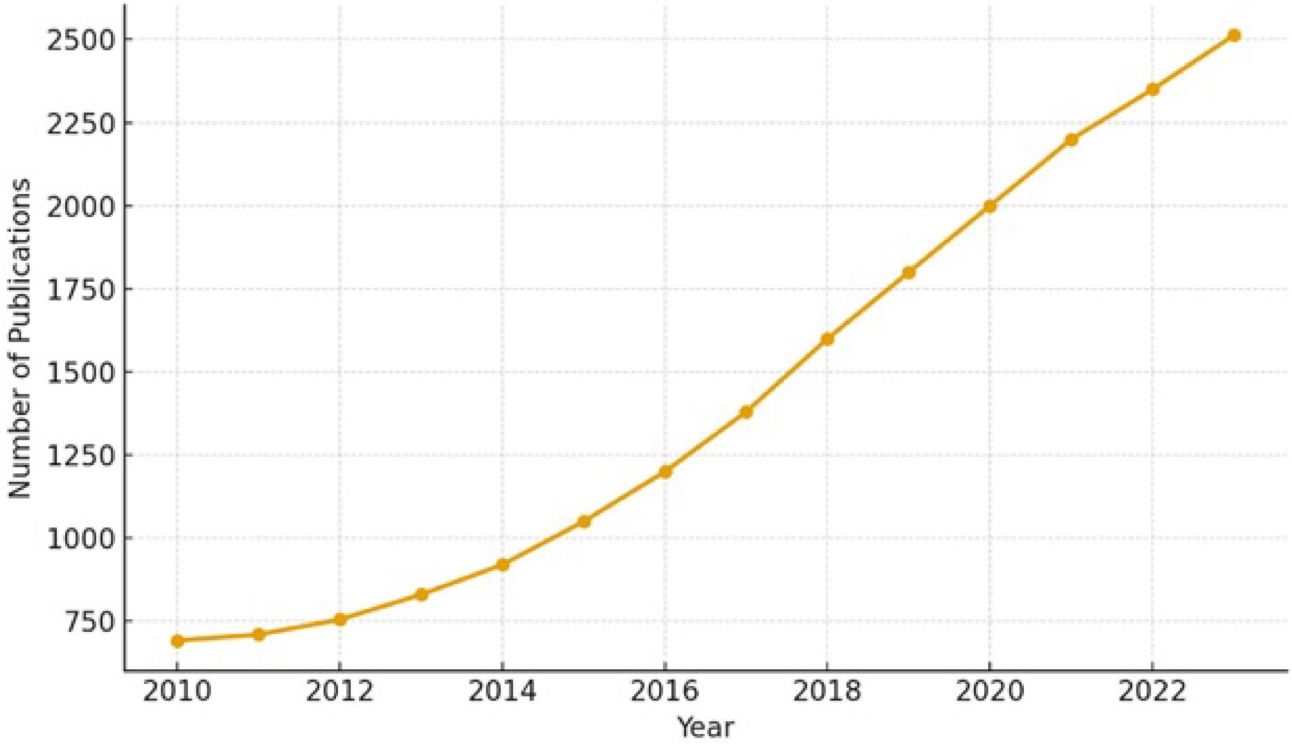

Fig. 1 Number of publications on dietary fibre research from 2010 to 2023, based on bibliometric data in Web of Science database (depicted from [119])

foods’, ‘Fibre fortification’, ‘Prebiotic dietary fibre’, and ‘technological properties of dietary fibre’.

Sources and classification of dietary fibres

Whole grains (barley, wheat, corn, rye), pseudocereals (millet, quinoa, sorghum, coix seed, oats, teff, amaranth, chia, and fonio) [12, 13], legumes (beans, peas) [14], seeds (chia seed, hempseed, linseed, poppy seed, pine nut, sesame, hot pepper, pumpkin and sunflower seeds) [14, 15], fruits and vegetables (banana, citrus, orange, peach, grapes, guava, mango, passion fruit, papaya, carrot, pea, tomato, pumpkin, potato, cauliflower, garlic, onion, and kiwifruit) [16–18], nuts [19], and mushrooms are potential sources of DFs. The DF content of these food materials ranges from 1 to 45% depending on the source and type of them. Cereal brans and whole grain cereals have gained significant attention since they contain diverse fibres. Fruit by-products contain both soluble DF and insoluble DF, with reduced phytic acid and caloric value [20].

Researchers classify DFs according to ‘insoluble’ or ‘soluble and fermentable’ [21] (Fig. 2). The types of DF are resistant starch, crude fibre (the residue remaining after sequential treatment of a food sample with dilute acid and dilute alkali) [1], hemicellulose, non-starch polysaccharides, cellulose, arabinoxylan, pectin, β-glucans, mucilage, gums, lignin, and oligosaccharides (notably fructans) [22]. DFs can be classified according to their viscous nature (viscous and non-viscous), structure (non-linear and linear), fermentability (fermentable and less/non-fermentable), solubility (soluble and insoluble), and physiological effect (Table 1). Solubility and fermentability are the most extensively studied classifications [20]. The soluable DF and insoluable DF fractions are based on their ability to be dissolved or extracted in aqueous solutions. insoluable DFs are mainly composed of cell-wall components (e.g., cellulose, chitosan, hemicellulose, lignin, and some RS), whereas soluable DFs consist of non-cellulosic polysaccharides and secretions in the cell wall (e.g., pectin, gums, mucilage, inulin, β-glucans) [12, 23].

The non-viscous and insoluable DFs (cellulose, hemicelluloses and lignin) are mostly found in cereal grains including wheat and corn and, in some vegetables, while the viscous gel forming and soluable DFs such as some storage polysaccharides, pectin, gums, and algal polysaccharides are found in beans, barley, oats, vegetables, fruits, and algaes [24].

Extraction of dietary fibres

The extraction of DFs from plant sources involves various techniques that influence their composition, structure, and functional properties. These methods determine the efficiency of fibre recovery and the quality of the extracted material, impacting its application in food systems. Extraction approaches are generally classified into chemical, enzymatic, and physical or emerging “green” techniques, each with distinctive mechanisms, advantages, and limitations. The choice of extraction method affects not only the solubility profile and structural integrity of DFs but also the

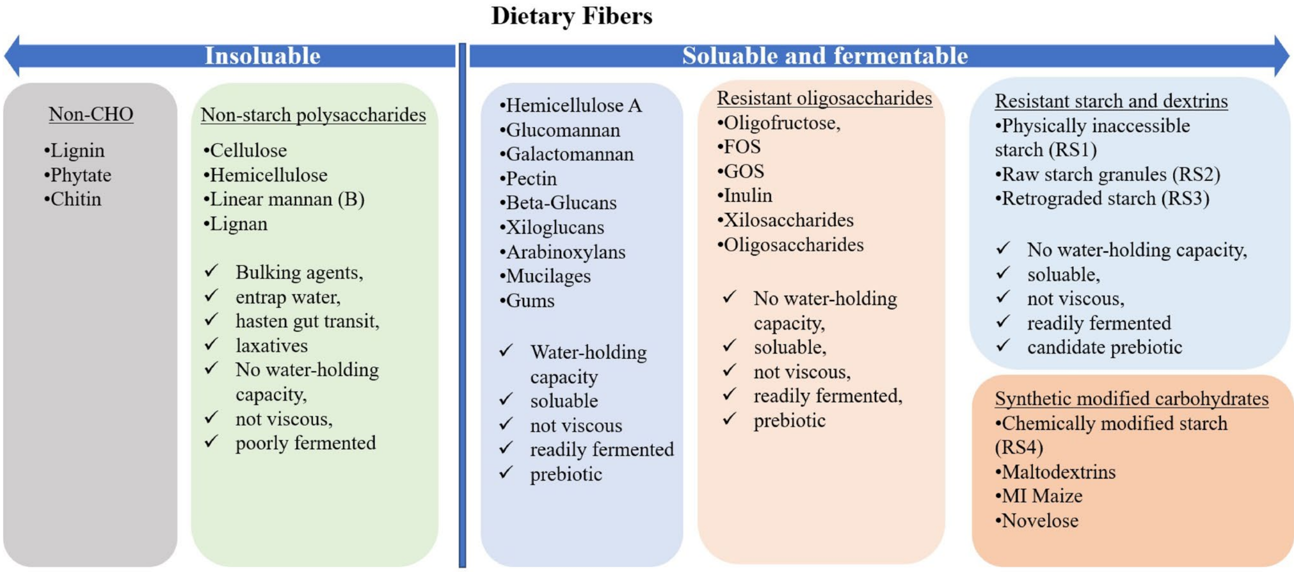

Fig. 2 Sources and classification of dietary fibres. Adapted from: [88, 89, 120].

Table 1 Classification of dietary fibres by solubility, viscosity, and fermentability

Category	Examples	Physiological Effects	Food Sources	Evidence Level
Soluble, viscous, fermentable	β-glucans, psyllium, pectin, gums, inulin	Delay gastric emptying, reduce LDL cholesterol, lower postprandial glucose, support SCFA production	Oats, barley, citrus fruits, legumes	Strong (meta-analyses support cholesterol & glycaemia benefits)
Soluble, non-viscous, fermentable	Fructooligosaccharides, galactooligosaccharides	Prebiotic effects (increase bifidobacteria, lactobacilli), enhance mineral absorption	Onions, garlic, bananas, asparagus	Moderate (systematic reviews support prebiotic function)
Insoluble, non-viscous, poorly fermentable	Cellulose, lignin	Increase stool bulk, reduce intestinal transit time, prevent constipation	Wheat bran, whole grains, nuts, some vegetables	Strong (consistent evidence for laxation)
Insoluble, partially fermentable	Resistant starch (RS2, RS3), some hemicelluloses	Improve insulin sensitivity, enhance SCFA (esp. butyrate)	Legumes, unripe bananas, cooked-cooled potatoes	Moderate (evidence varies by RS type)

retention of bioactive compounds, which are often sensitive to processing conditions [12].

Physical extraction methods involve mechanical processing such as milling, sieving, and ultrasonication to isolate fibre fractions from plant materials [25]. Novel “green” extraction methods including ultrasound-assisted extraction, microwave-assisted extraction, high-pressure processing, subcritical water extraction, and pulsed electric field, have recently gained attention as sustainable alternatives that reduce chemical inputs and improve process efficiency. Ultrasound-assisted extraction and microwave-assisted extraction enhance mass transfer through cavitation and dielectric heating, respectively, accelerating cell wall disruption and improving extraction yield and solubility of DFs [26]. Subcritical water extraction, which employs water under elevated temperature and pressure, exploits water’s tunable polarity to efficiently solubilise hemicellulosic fractions and release SDF without organic solvents [27]. High-pressure and PEF-assisted extractions preserve thermolabile compounds and promote fibre swelling, enhancing functionality while maintaining nutritional integrity [28]. The primary advantages of these physical methods are their short processing time, reduced solvent use, and minimal degradation of bioactives. Nonetheless, the need for specialised equipment, high energy input, and challenges in process scale-up are notable disadvantages [29].

Chemical extraction methods utilize acids, alkalis, or organic solvents to break down plant cell walls and release fibre components. Researchers commonly use acid hydrolysis to remove non-fibre components of extracted DFs. However, harsh chemical treatments may lead to structural degradation and loss of bioactive compounds. Acidic extraction with mineral acids such as HCl or H_2SO_4 effectively hydrolyses hemicelluloses and removes non-fibre components, while alkaline extraction using NaOH or KOH disrupts lignin–carbohydrate complexes, enhancing fibre accessibility and swelling capacity [12, 30]. These methods are advantageous for producing high yields of insoluble dietary fibre and facilitating delignification, particularly in lignocellulosic residues. However, the use of harsh reagents often leads to partial depolymerisation and loss of functional groups, reducing viscosity and gel-forming capacity [26]. Moreover, residual chemicals, colour changes, and environmental pollution due to reagent disposal present significant drawbacks that limit industrial scalability and sustainability [29].

Enzymatic extraction methods provide a milder and more selective approach by employing enzymes such as cellulases, hemicellulases, and pectinases to hydrolyze specific components of plant cell walls. Researchers widely regard enzymatic extraction methods as eco-friendly due to their specificity and minimal impact on the nutritional value of fibres [31]. This approach preserves the molecular integrity of polysaccharides, maintains their branching and molecular weight, and enhances the proportion of soluble dietary fibre, thereby improving prebiotic potential and fermentability [31, 32]. Enzymatic hydrolysis is environmentally friendly and operates under moderate conditions, resulting in minimal nutrient loss and high-quality fibres with improved water-holding capacity and viscosity. However, the relatively high cost of enzymes, longer processing time, and incomplete digestion of structural polysaccharides limit its large-scale adoption [27, 28]. Comparative studies on walnut flour and kiwifruit residues have shown that enzymatic and enzyme-assisted mechanical treatments yield fibres with more porous and honeycomb-like structures and higher hydration properties than chemically extracted fibres [33, 34].

The composition and structure of extracted DFs influence their functional properties, including water retention, viscosity, and gel formation. The ratio of soluble to insoluble fibres affects their application in food systems, as soluble fibres contribute to viscosity and gelation, while insoluble fibres improve textural attributes. The presence of bioactive compounds such as polyphenols and flavonoids in extracted fibres enhances their antioxidant capacity, providing additional health benefits. However, the concentration of bioactive compounds in DFs can sometimes be low, making their industrial application less effective unless highly concentrated extracts are used. While the bioactive compounds found in dietary fibers may not always be present in sufficiently high concentrations to deliver therapeutic effects on their own in whole food forms, their extraction, concentration, and incorporation into industrial products can make them highly relevant. The extraction method used significantly impacts the retention of these bioactive compounds and the overall nutritional quality of the fibre [27].

Hybrid or combined extraction techniques, such as enzyme-assisted ultrasound or microwave-assisted alkaline extraction, have shown synergistic effects by coupling mechanical disruption with biochemical specificity. These integrated methods improve fibre yield, solubility, and bioactive retention while reducing process severity [31]. For instance, ultrasound-assisted alkali extraction of pea peel fibres resulted in significantly higher WHC and oil-holding capacity compared to single-step methods [12]. Similarly, combined subcritical water and enzymatic treatments have enhanced both extraction efficiency and the retention of phenolics, contributing to fibres with superior antioxidant potential [27]. However, combined methods increase operational complexity and equipment cost, necessitating optimization of parameters such as temperature, pH, and solids loading for reproducibility.

DFs extracted using different methods have applications in a wide range of food products. In bakery products, fibres improve dough properties, enhance moisture retention, and extend shelf life [33]. In dairy and plant-based alternatives, they contribute to creaminess, stability, and mouthfeel. Meat analogs benefit from the water-binding and textural properties of fibres, improving their resemblance to conventional meat products [35, 36]. Functional beverages utilize soluble fibres to enhance viscosity and provide prebiotic benefits, supporting gut microbiota [28].

Current coverage catalogs many matrices and techniques, but a stronger synthesis should contrast head-to-head extraction routes across comparable raw materials (e.g., hot-compressed/subcritical water vs. alkaline/enzymatic vs. ultrasound-assisted) using harmonized endpoints (yield partitioning into soluable DF/insoluable DF, co-extracted phenolics, process mass intensity, and techno-functional outcomes) [37]. Studies optimized within a single matrix (citrus peel, passion fruit seed) are not readily comparable due to disparate conditions and response metrics; a meta-framework is needed that normalizes solids loading, pH/ionic strength, thermal history, and particle size prior to testing functionality [29]. Scale-up and environmental performance (energy/water footprints, solvent recovery) of 'green' extractions such as subcritical/hot-compressed water remain underreported and should be benchmarked via life cycle assessment alongside classical chemical routes. Finally, the prebiotic selectivity of extracted fractions is rarely linked back to extraction chemistry (e.g., branching, uronic acids); future work should integrate extraction–structure–microbiome triads with standardized in vitro fermentation models and targeted in vivo readouts.

Modification of dietary fibres

The modification of DFs aligns with the growing interest in functional food ingredients that support consumer demand for health-promoting products [38]. By tailoring the physicochemical properties of DFs, food manufacturers can design products with improved texture, stability, and nutritional profiles. Food manufacturers use modified DFs as fat replacers, stabilizers, or texturizers in a range of formulations. Moreover, their enhanced solubility and swelling behaviour can contribute to satiety and glycemic control, supporting dietary interventions aimed at managing obesity and diabetes. From a health perspective, improving the bioavailability and fermentability of fibres through modification could potentiate their prebiotic activity, thereby supporting gut microbiota composition and overall gastrointestinal health. In addition, some fibres may have unpleasant taste, texture, or smell attributes. Modification could overcome these disadvantages to improve acceptance [39]. However, it is essential that such modifications preserve the integrity of the fibre's nutritional value and do not generate undesirable byproducts. The main modification strategies applied to a DF preparation are physical, chemical, biological, and multi-methodological combination approaches to modify or improve fibre functionality (Table 2) [40].

Enzymatic treatment

Enzymatic treatment is a widely used technique for altering the molecular structure of DFs by targeting specific polysaccharide bonds [41]. Researchers subjected DFs to enzymatic hydrolysis using such as pectinase, xylanase, and cellulase (Table 2). These enzymes act on the pectic and cellulosic components of the fibre matrix, facilitating partial depolymerization and structural rearrangement. In a study, enzymatic hydrolysis of tomato peels using viscozyme L increased soluble DFs, along with enhanced galacturonic acid content, hydration capacity, glucose absorption, and lycopene concentration [32]. Enzymatic modification significantly improved the solubility of DFs [41]. They stated that the enhancement can be attributed to the breakdown of complex polysaccharides into shorter, more hydrophilic

Table 2 Modification of dietary fibre with physical, chemical, biological, and multi-methodological combination approaches

Sources of DFs	Approaches	Modification Conditions	Significant characteristics	References
Physical approaches				
Wheat bran (coarse bran)	Steam explosion	Steam temperatures: 120–160 °C, Residence time: 5 and 10 min, Pressure: 0.9, 2.3, 3.5, 5.0 bar	High steam temperature and long residence duration enhanced carbohydrate solubility. The steam explosion, followed by enzyme treatment, improved fibre solubility and quality in bread. The phytic acid level in bread was reduced by steam explosion	[41]
Rosa roxburghii pomace	Steam explosion	0.87 MPa for 97 s	Soluble DF content increased, whereas insoluble DF content declined. The modified insoluble DF had better thermal stability. Steam explosion treatment significantly increased the oil-holding capabilities of insoluble and soluble DF as well as the hydration capacity of insoluble DF	[61]
Dried okra seeds (*A. esculentus* [Linn.] Moench)	Steam explosion	1.0, 1.5, and 2.0 MPa for 5 min	The crystallinity and water retention values of the fibre were increased. The release of nutritional fibres and lipids from okra seed flour was enhanced. The release of total phenolics with antioxidant strength, free radical scavenging activity, and ferric-reducing antioxidant power were also improved	[121]
Flammulina velutipe	High-pressure homogenization	High-pressure homogenization for 0, 10, 30, and 50 cycles at 700 bar, 4–60 °C, and pH 3 to 7	Water-insoluble DFs demonstrated higher water holding capacity and stability emulsification performance and interfacial properties	[45]
Bean dregs	Ultrafine grinding; High pressure; Microwave; High temperature cooking; These both combination	Ultrafine grinded at 30 Hz; High pressure at 300 MPa for 10 min; Microwave oven at medium heat levels for 4 min; Vertical high-pressure Steam sterilizer at 115 °C for 25 min.	Ultrafine grinding combined individually with the other three treatments can significantly decrease viscosity. Ultrafine grinding and high-pressure combination treatment had the highest stability for the bean dreg slurry. The amount of bound water in bean dregs rose following the high-temperature cooking ultrafine and grinding combined individually with the other three treatments, whereas the amount of immobile water was reduced	[44]
Grape pomace cv. 'Malbec' (*Vitis vinifera* L.),	Micronization	Samples were milled at different rotational speeds with 300, 375, and 450 rpm at 30, 60, and 90 min. Particle sizes were diameters 10, 50, and 90 µm.	Insoluble DF has been broken down, and their concentration diminished. This higher soluble DF content showed the redistribution of fibre compounds. The particle size was significantly reduced by ball milling. The solubility of the milling powder was enhanced. Water holding, oil holding, and cation binding capacities of milling powder were reduced. Micronization improved the Extraction of phenolic compounds, primarily catechin and epicatechin	[42]
Rice bran	Thermal Extrusion	Screw speed at 250 rpm/min and the extrusion cooking temperature between 100–180 °C.	The extrusion cooking temperatures at 100 °C and 120 °C increased soluble DF's water and oil retention capacity, water solubility, antioxidant capacities, and in vitro bile salt, cholesterol, and glucose capabilities. While the material moisture concentrations were 11% and 14%, soluble DF had stronger in vitro binding and antioxidant capabilities	[59]
Sweet potato residues	Twin-screw extrusion	Screw speed at 180 rpm, feed rate at 17 Hz, feed moisture at 40%, and extrusion temperature at 150 °C	Soluble DF levels, cholesterol and sodium cholate adsorption ability, radical scavenging activity, and digestive enzyme inhibition increased. Extrusion decreased the particle size and molecular weight of soluble DF, regulated monosaccharide ratios, and enhanced thermal stability and the capacity for retaining water, oil, swelling, and glucose absorption. The macromolecules of soluble DF were fractured down into smaller fractions and formed a porous shape after extrusion	[59]

Table 2 (continued)

Sources of DFs	Approaches	Modification Conditions	Significant characteristics	References
Chokeberry (*Aronia melanocarpa*) pomace powder	Twin-screw extrusion	Specific mechanical energies in the range of 145–222 Whkg^{-1} and material temperatures (T_M) in the range of 123–155 °C	high molecular weight contents of soluble DF did slightly rise with increasing thermomechanical stress. The amounts of pectic polysaccharides in the soluble and insoluble DF fractions changed due to extrusion. The content of thermolabile anthocyanins decreases proportionally with 222 Whkg^{-1} and 155 °C	[60]
Commercial plant fibre (citrus fibre, apple fibre, oat fibre, and pea fibre)	Ultrasound	Ultrasound with 150 s amplitude at 116 µm, energy density at 225 kJ/l, and power 325 W.	Ultrasound effectively emulsified fibre into small droplet sizes and modified the techno-functional properties of DF. Plant fibre containing high amounts of soluble DF caused higher initial in-vitro fat degradation	[46]
Tea seed	Ultrasound	Puried fibreevenly dispersed in distilled water (1:100 w/w) under ultrasound treatment at 40 °C, 640 W for 20 min	Ultrasonically treated fibre displayed higher capacity, oil-binding capacity, swelling capacity, emulsification activity, and emulsification stability. The adsorption ability of enzymatically hydrolyzed fibre and enzymatic-ultrasonic treated fibre for cholesterol, glucose, and nitrite ions while simulating the gastrointestinal system was also enhanced	[47]
Sugarcane	Microwave irradiation; Ultrasound; High-pressure homogenization	Microwave irradiation at 5% and 10% sugarcane fibre for 5 and 10 min; ultrasound at 30% amplitude at 7% sugarcane fibre for 1.5–3 h; high-pressure homogenization at 1% sugarcane fibre, 2000 bar for 1 or 2 passes	The largest size of particles and highest water and oil holding capability were found in sugarcane fibre treated with high-pressure homogenization at 2000 bar for 2 passes. All physical treatments could lower hemicellulose and enhance cellulose content in sugarcane fibres. The bread demonstrated the firmest texture when using sugarcane fibre with 2-pass high-pressure homogenization and 15-min microwave irradiation treatment. The glycemic response eventually decreased in all physically treated breads	[43]
Carrot	Microwave; Ultrasonic; High-pressure cooking	Microwave oven at 80 °C and 600 W for 45 min; Ultrasonic treatment for 15 min with 500 W at room temperature; High-temperature steam at 0.1 MPa and 121 °C for 20 min	The carrot powder modified with microwave and ultrasound displayed a rougher structure. Besides, ultrasonic carrot soluble DFs also revealed higher cholesterol absorption capacities, molecular weight, water holding ability, reddish and yellowish color	[48]
Chemical approach				
Okara	Alkaline hydrogen peroxide	2% hydrogen peroxide solution at 42 °C for 5 h.	The hydrogen peroxide-treated okara increased 601% of soluble fibre content, 26% of water absorption and holding capacity, and 609% protein solubility in water. The modified okara fibres particles exhibited a more rough exterior and a more fractured structure than the untreated fibres	[49]
Potato peel	Acid-alkali	Acid-alkali extraction in 1.5% acid and 1.6% alkali solution for 35 min	The yield of water-insoluble DF from potato peel could reach 12.6%	[50]
Papaya peel (*Carica papaya* Linn.)	Alkaline; Ultrasound-assisted alkaline	Ultrasonic time for 30.76 min and ultrasonic power at 175 W	The highest yield of soluble DFs with ultrasound-assisted alkaline treatment was 36.99%. Ultrasound-treated fibres had a lower level of total amino acid but a higher essential amino acid content. Besides, ultrasound-treated fibres decreased crystalline but increased thermal stability, water and oil holding ability, and swelling capacities	[51]

Table 2 (continued)

Sources of DFs	Approaches	Modification Conditions	Significant characteristics	References
Sorghum seeds (*Sorghum bicolor*)	Cross-linking; Carboxymethylation; Hydroxypropylation	Cross-linking using sodium trimetaphosphate/sodiumtripolyphosphate (99:1% w/w); Carboxymethylation using 2-propanol and chloroacetic acid; Hydroxypropylation using sodium sulfate and propylene oxide	These three treatments improved oil and water holding capacity, swelling ability, and soluble DF content, especially with carboxymethylation. All treatments increase in brown color, crystallinity, and thermal stability in sorghum DF	[52]
Wholegrain flours (brown rice and buckwheat)	Cross-linking; Carboxymethylation; Hydroxypropylation	Cross-linking using sodium trimetaphosphate/sodiumtripolyphosphate (99:1%); Carboxymethylation using 2-propanol and chloroacetic acid; Hydroxypropylation using sodium sulfate and propylene oxide	Carboxymethylation boosted soluble DF contents and water solubility. However, cross-linking and hydroxypropylation significantly enhanced the contents of insoluble DF, leading to decrease water solubility	[54]
Biological approach				
Tomato peels	Viscozyme L	5% (w/v) Viscozyme L solution at pH 6 with 1:10 (w/v) in the solid-to-liquid ratio for 35 min	The extraction yield of soluble DF from the tomato peels after enzymatic treatment was raised by 72.3% in comparison to the original tomato peels. Viscozyme L-treated fibres demonstrated a larger galacturonic acid content, a smaller molecular weight, and a lower zeta potential. These fibres also displayed a looser microstructure, higher hydration and glucose absorption capabilities, stronger gelling ability and higher lycopene content than untreated fibres	[32]
Potato (*Solanum tuberosum* L.) residue	*Trichoderma viride* cellulase; *Trichoderma viride* xylanas	0.18% cellulase/xylanase solution (cellulase (U): xylanase (U) = 1:1)	cellulase/xylanase treatment significantly enhanced the soluble DF content, soluble monosaccharide content, thermostability, and porous. Water and oil holding ability, swelling capacity, the absorption capacity of glucose and cholesterol, and cation exchange ability were also increased	[62]
Tea residues	*Trichoderma viride* fermentation	Fermentation for 43.59 h, pH 5.46, 28 °C, inoculum size 10.34%.	The yield of soluble DF from fermented tea residues increased by eight times. Fermented tea residues also enhanced uronic acid content, crystallinity, thermal stability, and binding capacity of lead, cadmium, and copper ions	[63]
Okara	*Monascus anka* fermentation	Fermentation at 28 °C, 160 rpm for 7 days, inoculum size 10%	The fermented okara is greatly enhanced in terms of oligosaccharides content, soluble DF content, swelling ability, as well as water and oil holding capacity	[64]
Rosa roxburghii pomace	*Bacillus natto* fermentation	Fermentation inoculum at 38.7 °C, pH 4.97 for 12 h and 4% concentration	The breakdown of cellulose and hemicellulose was observed in pomace fibres, leading in the production of a more porous lax structure. Water and oil holding, as well as cation exchange capacity were clearly improved	[122]
Millet bran	*Bacillus natto* fermentation	Fermentation with 3% inoculum at 37 °C, 180 rpm for 47 h	Soluble DF content increased from 2.3% to 13.2%, and the soluble/insoluble DF ratio rose from 3.1% to 19.9%. Fermentation caused cellulose and hemicellulose to break down, forming polysaccharides and more porous lax structures. Water and oil holding capacity, swelling capacity, and the ability to bind cholesterol, bile salts, nitrite ions, and glucose were all enhanced. Both the overall phenolic content and scavenging ability of free radicals dramatically improved	[66]

Table 2 (continued)

Sources of DFs	Approaches	Modification Conditions	Significant characteristics	References
Multi-methodological Combinations				
Orange peel	Homogenization; alkaline hydrogen peroxide treatment	30 MPa at 60 °C	The water holding capacity of citrus DF was dramatically enhanced after both treatments. The total DF content and thermal stability of citrus DF were also improved. The modified citrus DF had a porous structure, and its crystalline area might be disturbed	[55]
Grapefruit peel	Microwave; Sodium Hydroxide; Enzymes; Ultrasound; Microwave-combination	Microwave at 500 W and 80 °C for 40 min; 1% sodium hydroxide; Cellulase/substrate ratio of 30 U/g, α-amylase (1% g/g) papain (0.05% g/g); Sonicator at power 200 W for 10 min at 25 °C	The structures of the soluble DFs under three microwave-combined treatments were more complicated and loose. These fibres also presented a greater molecular weight, higher thermal stability, crystallinity, and a more varied monosaccharide composition. Water and oil holding capacity, cholesterol adsorption capacity, glucose adsorption capacity, and nitrite ion adsorption capacity were also significantly increased, particularly in microwave-ultrasonic treatment	[56]
kiwifruit (*Actinidia deliciosa*)	Acid (citric acid); Alkali (sodium hydroxide); Enzyme (amyloglucosidase and protease)	Kiwifruit and citric acid at a ratio of 1:40 (w/v) for 2 h of Extraction on the 40 °C water bath; sodium hydroxide solution for 2 h of Extraction on the 40 °C water bath; protease (500 µL, pH 7.5) for 1 h and amyloglucosidase (200 µL, pH 4.5) for 1 h in the 40 °C water bath	The DFs under acid and enzymatical treatment had looser and more complex structures. Insoluble DFs with alkali treatment demonstrated improved significantly thermal stability. DFs with acid treatment revealed larger molecular weights Enzymatical and acid treatment showed higher oil and water holding capacity, glucose and nitrite ion adsorption capacity, and bile acid binding capacity	[57]
Palm kernel expeller	Acidic treatment; Heating combined with enzymatic hydrolysis; Carboxymethylation; Hydroxypropylation	Acidic treatment: 1 mol/L NaOH (1: 10, w/v) at 60 °C for 2 h, and then 1 mol/L HCl at 60 °C for 30 min. Heating combined with enzymatic hydrolysis: hemicellulase and cellulase at pH 4.5, 50 °C for 3 h; Carboxymethylation using 2-propanol and chloroacetic acid; Hydroxypropylation using sodium sulfate and propylene oxide	All modifications increased soluble DF content, emulsifying ability, water swelling and retention capacity, viscosity, and α-amylase inhibitory activity. Carboxymethylation also significantly reduced the oil retention ability and brightness of fibres. The enzymatic hydrolysis with heating significantly enhanced oil retention ability. Acidic treatment decreased the oil and water retention ability	[58]

DF dietary fibre

chains that can more readily disperse in aqueous environments. Their findings indicates that enzymatic treatments can reduce polymer chain length and molecular weight, thereby enhancing hydration properties. Therefore, the WH and swelling capacities of the fibre were elevated. Similarly, cellulase and xylanase treatments of potato residue increased soluble DF and improved thermostability, water and oil retention, glucose and cholesterol binding, and cation exchange capacity through microstructural porosity [32]. The numbers of the following references need to be arranged accordingly). . Additionally, enzymatic degradation caused a modest reduction in particle size, reflecting partial fragmentation of the fibre matrix. This microstructural alteration potentially increases the surface area available for interaction with water and other components in food systems, further contributing to the improved functional behaviour observed. Enzymatic treatment may enhance the potential of DFs for applications in high-moisture food formulations, where solubility and swelling capacity are critical to product texture and mouthfeel.

Mechanical treatment

Mechanical treatment, particularly micronization by milling or high-shear homogenization, disrupt DFs physical structure and reduce particle size. This process relies on intense mechanical forces to break down agglomerated or fibrous particles into finer fragments, thereby increasing the surface area and modifying the spatial configuration of the fibre particles size [42, 43]. The mechanically treated DFs exhibited a notable reduction in particle size, resulting in a substantial increase in both WHC and OHC, while having a relatively minor impact on solubility [44]. In a study, it was reported that the high-pressure homogenization provided water-insoluble DFs had a higher water holding capacity and stability and better interfacial characteristics [45]. The increased WHC might be linked to the exposure of additional hydrophilic sites within the fibre matrix, which facilitates the binding of water molecules. Similarly, the enhanced OHC may be attributed to the formation of a more porous structure that can entrap lipophilic substances. The improved WHC and OHC observed in mechanically modified DFs suggest its suitability for incorporation into bakery, meat, and dairy analog products, where moisture and fat retention are essential for texture and stability. High-intensity ultrasound application have been employed to formulate emulsions incorporating plant DF and canola oil, resulting in enhanced physicochemical properties and modified in vitro digestibility. Ultrasound-induced reductions in oil droplet size and structural alterations in fibre contributed to increased viscosity and improved emulsion stability. Emulsions stabilized by fibres rich in soluble DF remained intact through in vitro digestion up to the intestinal phase, forming micelle-like structures [46]. Tea seed DFs were modified using ultrasound, enzymatic hydrolysis, and combined enzymatic-ultrasound treatments. Ultrasonically treated fibres exhibited superior WH, OB, swelling capacity, emulsification activity, and stability compared to other treatments. Moreover, enzymatically hydrolyzed and combined-treated fibres demonstrated enhanced adsorption of cholesterol, glucose, and nitrite during simulated gastrointestinal conditions [47]. Similarly, ultrasound- and microwave-modified carrot fibres displayed higher cholesterol-binding, molecular weight, and WHC [48]. In sugarcane fibre, high-pressure homogenization most effectively improved hydration properties and glycemic response in bread formulations [43].

Chemical modification

Chemical modification of DF can be achieved using agents such as acid, alkali, alkaline hydrogen peroxide, disodium phosphate, and through reactions like cross-linking, carboxymethylation, and hydroxypropylation. These treatments can convert insoluble DFs into soluble forms with enhanced physiological functionality by manipulating variables such as temperature, reagent concentration, and reaction duration. For instance, alkaline hydrogen peroxide treatment of okra significantly increased soluble fibre, water absorption, and protein solubility under optimal conditions [49]. Acid-alkali extraction of potato peel yielded 12.6% water-insoluble DF [50], while ultrasound-assisted alkaline extraction of papaya peel produced 36.99% soluble DF with improved functional and structural attributes [51]. Sorghum DF subjected to cross-linking, carboxymethylation, and hydroxypropylation showed enhanced hydration properties, thermal stability, and crystallinity, with carboxymethylation yielding the highest soluble DF content [52–54]. Citrus DF underwent homogenization and alkaline hydrogen peroxide treatment to enhance its physicochemical attributes. Both treatments significantly improved swelling capacity and WHC [55]. Grapefruit peel treated via microwave in combination with sodium hydroxide, enzymes, or ultrasound yielded DFs with more complex structures, increased molecular weight, higher thermal stability and crystallinity, and broader monosaccharide profiles. Microwave-ultrasound treatment yielded the highest enhancement in hydration properties and adsorption of cholesterol, glucose, and nitrite ions [56]. Kiwifruit DFs extracted using enzymes, acids, or alkali exhibited polysaccharide-specific IR spectra. Acid and enzymatic treatments produced more complex structures and better functional properties than alkali-treated samples, including enhanced bile acid binding [57]. Carboxymethylation, hydroxypropylation, heating, and enzymatic hydrolysis of palm kernel expeller DF improved its emulsifying ability, swelling capacity, viscosity, and α-amylase inhibition, while oil retention varied across treatments [58].

Thermal treatment

Thermal treatment (i.e. extrusion cooking) increased water and oil retention capacity, and water solubility by approximately 30–60% depending on the type of fibre [59, 60]. This high-temperature, high-pressure process can induce physicochemical changes in DFs through gelatinization, denaturation, or degradation of biopolymers. These changes are hypothesized to result from the partial loosening of the fibre matrix and increased porosity caused by thermal disruption. Such effects enable the fibre to absorb and retain larger volumes of water. In addition to functional improvements, a slight darkening in color might be observed, which may be associated with Maillard reactions or caramelization of residual sugars during heating. While this may influence the aesthetic quality of food products, it generally does not detract from the nutritional value or safety of the fibre. In another study, steam explosion treatment significantly increased the OB capabilities of insoluble and soluble DF as well as the hydration capacity of insoluble DF [61, 62]. The overall impact on solubility was less pronounced than that achieved through enzymatic treatment, indicating that thermal processes are less effective at breaking down complex carbohydrate structures unless applied under more severe conditions. The moderate improvements in hydration-related functionality and thermal stability render thermally modified DFs suitable for processed food applications involving heat, such as soups, sauces, and extruded snacks.

Microbial fermentation

Microbial fermentation can be used to alter structural and functional properties of DFs. Microorganisms including *Trichoderma viride*, *Trichoderma harzianum*, *Bacillus natto*, and *Monascus anka* are commonly employed. Fermentation of tea residues with *T. viride* enhanced soluble DF yield, thermal stability, crystallinity, uronic acid levels, surface area, and the ability to bind heavy metals such as lead, cadmium, and copper [63]. Liquid fermentation of okara with *Monascus anka* increased soluble DF content, improved swelling, and enhanced hydration and OB due to polysaccharide breakdown [64]. *Bacillus natto* fermentation significantly elevated soluble DF content in *Rosa roxburghii* pomace and millet bran, resulting in more porous structures, enhanced water and oil holding, and improved functional capacities such as antioxidant activity and glucose binding capacity [65, 66].

The comparative analysis of different modification techniques reveals distinct advantages and limitations associated with each method (Table 3). Combining enzymatic and heating and/or mechanical treatments could simultaneously improve both solubility and absorption capacities, broadening the scope of DF applications in complex food matrices [58]. Enzymatic modification consistently appears as the most effective strategy to enhance solubility and hydration capacity due to the targeted hydrolysis of complex polysaccharide linkages. Enzymes such as cellulase, xylanase, and pectinase act selectively on the fibre matrix, increasing soluble fibre content and improving viscosity, gelation, and binding capacities for bile acids, cholesterol, and glucose. These

Table 3 Comparative overview of dietary fibre modification methods, structural effects, techno-functional gains, trade-offs, and typical applications

Method	Primary Structural Effect	Techno-Functional Gain	Key Trade-Off/Limitation	Typical Applications	Key References
Enzymatic hydrolysis (e.g., cellulase, hemicellulase, xylanase, pectinase)	Selective hydrolysis of polysaccharide linkages, targeted depolymerization, reduction in DP, increased branching	High specificity, eco-friendly, preserves bioactives, fermentability, prebiotic potential, enhanced solubility, swelling, WHC	Cost of enzymes, incomplete hydrolysis, possible bioactive loss at prolonged treatment, requires precise conditions (pH, temperature)	Prebiotic ingredients, high-moisture foods, functional beverages	[32]
Mechanical/physical (micronization, milling, high-pressure, ultrasonication)	Particle size reduction, increased porosity, increased surface area, disrupted cell walls	Increased WHC/OHC, improved dispersion, emulsion stabilization, preserves native structure, clean-label, no chemical residues	Limited improvement in solubility, potential loss of phenolics, high energy demand	Bakery products (improved hydration, texture), meat analogs (fat retention), dairy alternatives	[42, 123]
Thermal (extrusion, steam explosion, microwave)	High temp/pressure disrupts matrix, increases porosity, matrix loosening, gelatinization, Maillard browning	Improved hydration, WHC, and OHC, textural stability in heated foods, suitable for industrial scale; enhances antioxidant release (via Maillard/caramelization)	Risk of color darkening, may cause taste changes; less effective than enzymatic for solubility; possible nutrient degradation partial degradation of heat-labile compounds	Extruded snacks, soups, sauces, bakery	[60, 61]
Chemical (alkali, acid, cross-linking, carboxymethylation)	Breakdown of cell wall polysaccharides, bond cleavage or substitution, introduction of functional groups	Conversion of insoluble to soluble fibre, enhanced viscosity/emulsification	Solvent residues, regulatory restrictions, label-unfriendly perception, risk of nutrient/bioactive loss, formation of undesirable by-products	Tailored functional ingredients, emulsifiers, stabilizers, fat replacers	[52, 124]
Microbial fermentation (*Bacillus*, *Monascus*, *Trichoderma*)	Enzymatic breakdown of polysaccharides, modify structure, increase solubility and porosity	Elevated soluble DF, improved antioxidant activity, mineral binding	Variability in strain performance, scalability challenges, extended processing time, requires safety control	Functional foods with added probiotic/prebiotic potential	[125, 126]

WHC Water holding capacity, *OHC* oil holding capacity enzymatically modified fibres show superior performance in high-moisture food systems, where swelling and hydration behaviour are critical for textural optimisation [32, 67]. In contrast, mechanical treatments including micronization, ultrasonication, and high-pressure homogenizatio, primarily induce physical structural disruption, resulting in reduced particle size, higher surface area, and greater exposure of hydrophilic sites. These changes enhance the water- and oil-holding capacities (WHC and OHC) and improve interfacial stability in emulsified systems, although they exert relatively minor effects on solubility compared to enzymatic methods [68, 69]. Thermal treatments such as extrusion and steam explosion have also been shown to improve hydration and thermal stability, yet their effectiveness is moderate and frequently accompanied by color alterations due to Maillard reactions or caramelization [70]. Chemical modification techniques, including alkaline hydrogen peroxide treatment and carboxymethylation or hydroxypropylation, effectively convert insoluble fibres into soluble forms with enhanced emulsification, swelling, and viscosity properties [71]. However, these methods often raise environmental and labeling concerns due to chemical residues. Emerging biological approaches, notably microbial fermentation with *Trichoderma*, *Monascus*, and *Bacillus* species, provide sustainable alternatives that increase soluable DF content, porosity, and bioactive compound retention, thereby improving both functionality and health-promoting attributes [72]. Overall, enzymatic modification remains the most selective and sustainable approach for improving solubility and hydration-related properties, while mechanical treatments are better suited for applications requiring enhanced WHC and OHC. Thermal and chemical treatments offer moderate-to-high gains in functionality but must be optimized to balance efficiency, product safety, and consumer acceptability. Moreover, synergistic hybrid strategies—such as combining enzymatic and mechanical or enzymatic and thermal treatments—have demonstrated potential for achieving complementary improvements in solubility, swelling, and interfacial properties, suggesting that process integration could provide a more versatile design framework for DF powder development.

Dietary fibre powders

DF powders are solid particles with sizes ranging from 50 to 1000 µm. Particle characteristics, such as particle size, density, porosity, shape, diameter, hardness, and stickiness, or bulk characteristics, such as bulk density, flowability, compressibility, particle size distribution, and moisture content, are used to categorize food powders. Physical (size, shape, density, porosity) and chemical characteristics (composition, interactions with other substances, instant properties) are important properties affecting reconstitution behaviour (i.e. wettability, sinkability, dispersability, solubility) of food powders (Fig. 3) [73]. Food producers incorporate DF powders into baked goods, cereals, and snacks to lower the calorific value, to improve digestibility, and to provide prebiotic effect. Additionally, they play a crucial role in the formulation of nutraceuticals and pharmaceuticals, contributing to the development of functional and health-promoting products [74].

VOSviewer was used to visualize research mapping related to DF powders. Network visualization depicts the relationship between terms in the topic of DF powders which is connected by various lines to form a network [75]. Figure 4 exhibits the network visualization of similarities analysis of scientific papers published in Web of Science database between 2010 and 2024 with key word "DF powder" (1965 papers in total, minimum number of occurences of a term:12). Research mapping with VOSviewer highlights three main clusters of dietary fibre powder research between 2010 and 2024. The first cluster relates to particle and powder properties (e.g., size, densities, microstructure, hydration capacity, porosity). The second cluster connects DF powders with nutrition and health-related terms such as prebiotics, fermentation, metabolism, and cholesterol. The third cluster links DF powders to textural and sensory properties in food applications, including bread, biscuits, and emulsions. These clusters indicate that the literature has primarily focused on techno-functional properties, nutritional effects, and sensory/textural impacts in food systems.

Powder production methods

Powder production is a critical downstream operation that converts extracted dietary fibres into a stable, handleable ingredient; the chosen method strongly influences particle morphology, bulk density, rehydration, and retention of heat-sensitive bioactives. DF powder production methods vary depending on the type of powder being produced and the desired characteristics. DF powders are produced using various methods after extraction and refinement of the fibre from different sources. Common methods used in the production of DF powders include spray drying, freeze drying (lyophilization), milling/grinding, agglomeration, and encapsulation. These methods include physical treatments such as washing, boiling, pressure cooking, and solvent extraction. Other production methods may involve heat treatment and chemical technologies to modify the properties of the plant fibres [76]. These production methods aim to reduce the fat content in the fibre, increase hydration properties such as water holding and swelling capacities. Each method has its advantages and disadvantages, and the

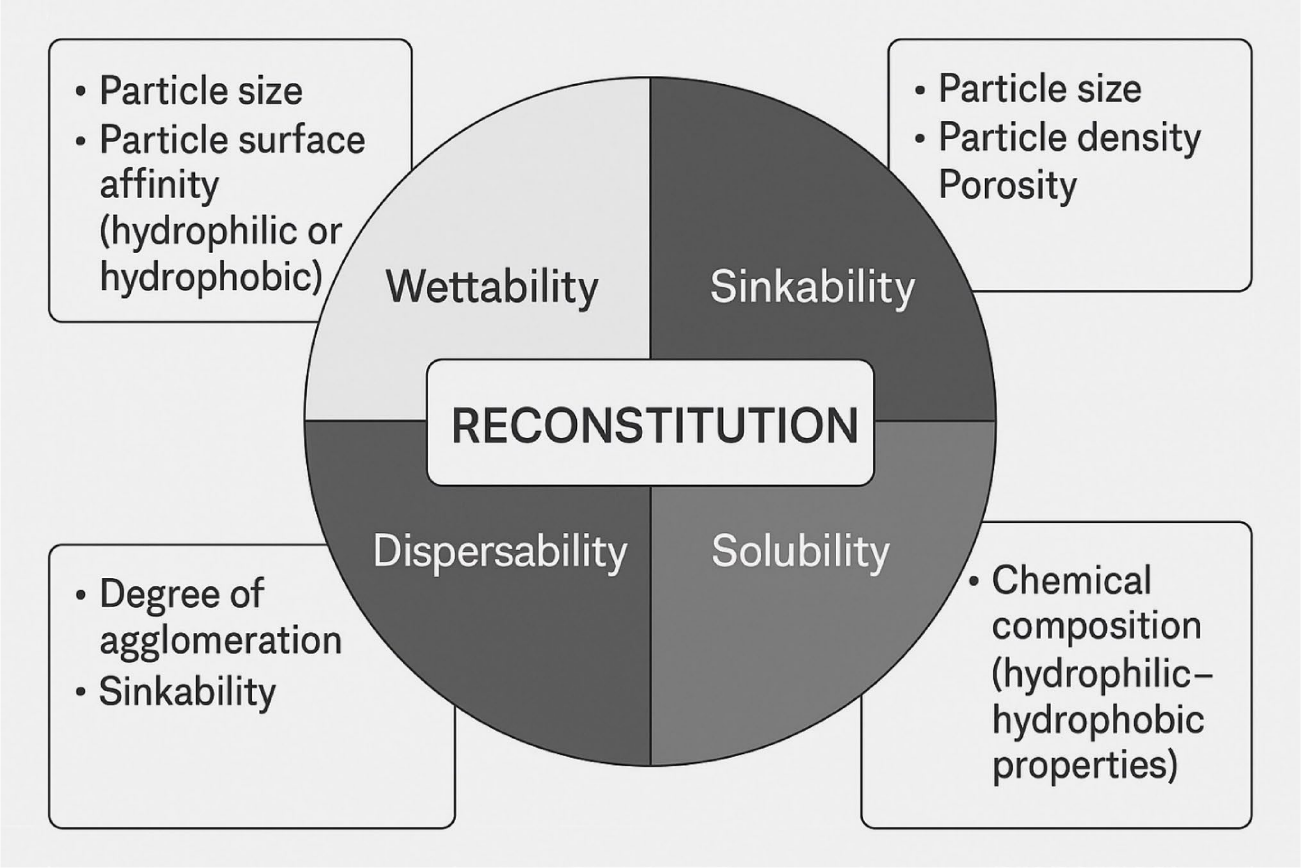

Fig. 3 Powder properties affecting reconstitution of dietary fibre powders

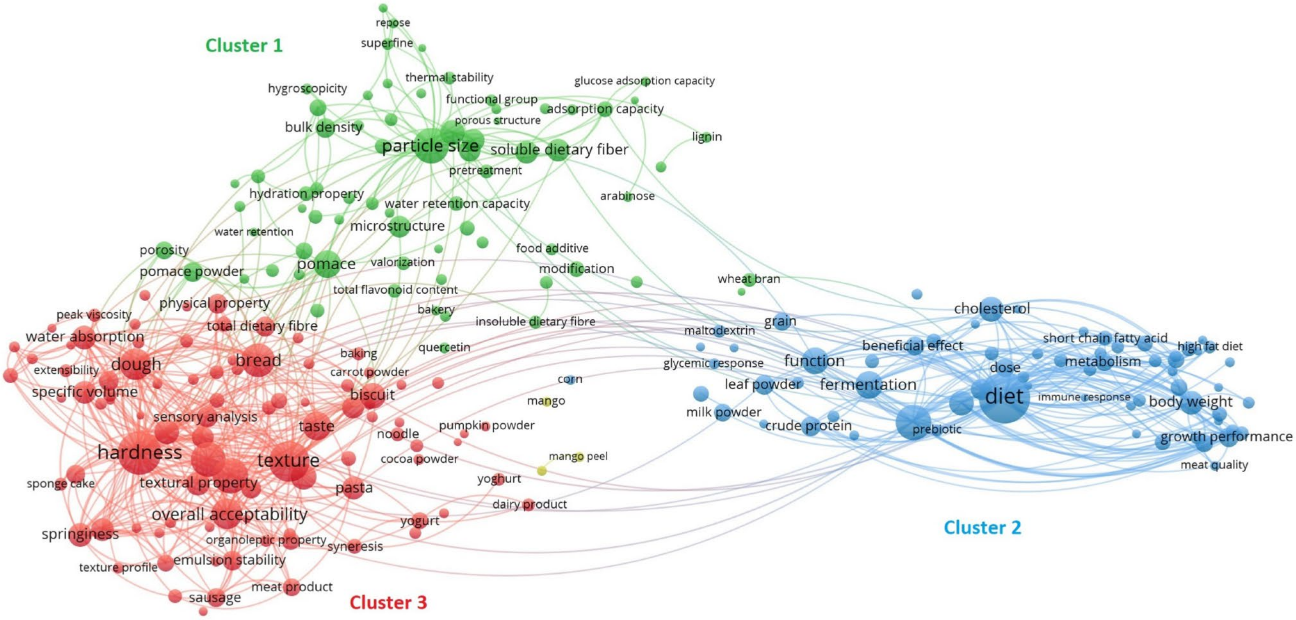

Fig. 4 VOSviewer network visualization map of co-occurrences of words in papers published in Web of Science in between 2010–2024 with key word “dietary fibre powder” (1965 papers in total, minimum number of occurrences of a term:12)

choice of method depends on factors such as the properties of the ingredients, desired characteristics of the final product, and production scale [77].

Spray drying is the industrially dominant approach for converting aqueous fibre slurries into fine powders because it offers high throughput, tunable particle size and moisture content, and relatively low cost per unit dried at scale; however, high inlet/outlet temperatures can degrade thermolabile phenolics and vitamins, and very fine spray-dried particles often suffer from poor flowability and increased hygroscopicity unless carriers (e.g. maltodextrin) or anti-caking agents are used [77]. Freeze-drying (lyophilization) preserves microstructure, porosity and sensory/nutritional quality to a greater extent than convective and spray methods - yielding powders with superior rehydration, water-holding and oil-holding capacities - but it is time-consuming, energy-intensive and economically feasible mainly for high-value, small-batch products [76]. Simple mechanical comminution (milling/grinding followed by sieving) is flexible and cost-effective for producing a range of particle sizes and is appropriate when the starting material is already dry; nevertheless, high-speed milling can generate heat and fines that reduce flowability and may cause oxidative changes unless cooling and controlled classification are applied [25]. Foam-mat and carrier-assisted drying methods improve drying rate and protect sensitive constituents by increasing surface area and using protective matrices, often producing low-density powders with rapid reconstitution, yet they require foaming/stabilizing agents that add formulation complexity and can impair reproducibility or sensory properties if not optimized. Emerging and hybrid approaches (e.g. spray-freeze drying, microwave- or infrared-assisted drying, or combinations of drying plus encapsulation) can mitigate some trade-offs - balancing throughput, bioactive retention and powder functionality - but introduce greater equipment complexity, scale-up challenges and capital costs that must be justified by the target application [12, 77]. In practice, method selection therefore represents a balance between desired techno-functional attributes (porosity, water holding and oil holding capacities, solubility, particle size distribution), cost and throughput constraints, and the need to preserve bioactive components; combinations of gentle drying with protective carriers or post-processing classification often deliver the best compromise for producing fibre powders tailored to specific food applications.

Properties of dietary fibre powders

The properties of DF powders may vary depending on the source, chemical composition, production method, and intended use. Some key properties to consider include chemical composition, the presence of soluble and insoluble fibre fractions, particle size and shape (Fig. 5), particle size distribution, tapped and bulk density values, flowability, hygroscopicity, solubility, porosity, and color [78]. These properties can affect the texture, hardness, flavor, and overall functionality of the food formulations [76]. Table 4 summarizes the DF powder properties reported by the previous research papers found in the literature.

Particle size of DFs plays and important role in physical and sensory attributes of food products. In addition, the size of the DF particles affects the digestive tract events such as transit time, fermentation, and fecal excretion. The size range of particles depends on the type of cell walls of the plant material and the type of powder production method. Digestive processes may modify fibre particle size during transit in the digestive tract as a result of chewing, grinding and bacterial degradation in the large intestine. A reduction in the particle size of grinded coconut residue from 1120 to 550 µm resulted in increased hydration properties and fat absorption capacity [3]. The researchers attributed this behaviour to increasing surface area and total pore volume as well as structural modification. However, they found out that further decrease in particle size below 550 µm resulted in decreased hydration properties [17]. obtained Grapefruit and Orange DF powder having D_{50} value ranged from 132.84 to 244.47 µm and specific surface area ranged from 1.35 to 23.00 m^2/g (Table 4).

It was reported that the surface chemistry of DF particles may affect some physiochemical properties such as adsorption or binding of some molecules, while the availability to microbial degradation (fermentation) of DFs is influenced by surface physical properties, surface area and porosity of the particles. The particle size and surface characteristics can be modified by powder production method and the source of DF [3]. The particle shape and surface properties of dietary fiber (DF) powders may vary depending on the source and the method of powder production. The particles are predominantly flaky and dendritic in shape, exhibiting irregular surface characteristics [17, 18, 79, 80].

The physical properties of DF powders, which affects the hydration properties, can be modified by processes such as drying, grinding, extrusion cooking or heating. The physiological behaviour such as formation of fecal bulking and induction of fermentation of DF in the digestive tract depend on the hydration properties of DF powders (i.e. swelling and water retention capacity). The pore volume of particles affects water absorption. The hydration characteristics of DF powders can also be influenced by temperature, pH, dielectric constant, ionic strength, and nature of the ions of the surrounding media. An increase in hydration capacity of extrusion processed corn meal and oatmeal was also reported. In a study, orange peel and pulp had around 79 and

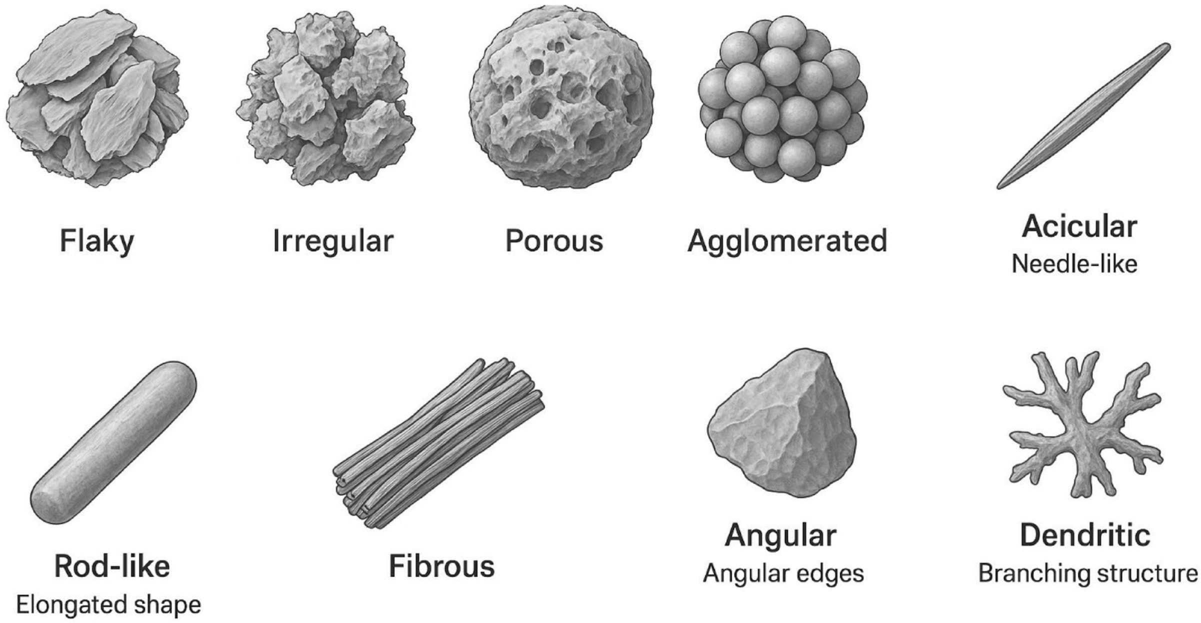

Fig. 5 Illustration of the various shapes of dietary fiber particles

Table 4 Dietary fibre powders from different sources and their functional properties

	WHC (g/g)	OHC (g/g)	SC (mL/g)	EC (%)	BD (g/cm3)	S (g/g)	SSA (m2/kg)	AoR (o)	PSR (µm)	References
Grapefruit peel pomace	28–31	6.6–8.8	16–24	-	-	-	-	-	-	[17]
Passion fruit seed powder	2.2–3.1	3.4–4.1	7.5–15.7	39–50	0.5–0.7	-	-	-	-	[18]
Turmeric residue powder	4.3		~ 8		0.412-	46% (WSI)	366	-	3–340	[83]
Jerusalem artichoke powder	4.8–5.9	-	2–6	-	0.34–0.39	0.22–0.42	-	-	-	[127]
Millet bran powder	2.15	~ 2	-	-	0.33-	-	1623	50	2.0–54	[82]
Pineapple peel powder	~ 6	2.03	1.62	-	0.76-	-	-	-	-	[84]
Tartary Buckwheat Leaf Powder	5.30–6.65	-	3.25–5.23	-	-	-	1058 − 496		3–13.6.6	[128]
Bitter melon polysaccharides	0.18–0.66 (%)	4.55–5.13 (%)	4.12–5.11 (%)	-	-	47–60 (%)	-	-	-	[129]
Java tea-leaf powders	2.5	-	-	-	0.32–0.45	-	0.8–1.1	32–37	168–502	[130]
Langra Mango Peel Powder	4.7	1.47	-	-	-	-	-	-	-	[131]
Jackfruit rind powder	3.1	2.4	-	-	-	-	-	-	-	[132]
Carrot pomace powder	4.61	1.87	-	-	0.47	-	-	-	-	[133]
DF powders from different sources	5–17 (%)	-	5.0–45	25–62	-	-	-	-	10–120	[80]

DF dietary fibre, *WHC* water holding capacity, *OHC* oil holding capacity, *SC* swelling capacity, *EC* Emulsion capacity, *BD* Bulk density, *S* solubility, *SSA* Specific surface area, *AoR* angle of repose, *m PSR* Particle size range, *WSI* water soluable index

71% DF with more proportion of insoluable DF having high water and oil holding capacity [3].

The solubility of DF powders has major effects on fibre functionality. It is reported that soluble viscous DF particles (mostly polysaccharides) can facilitate the digestion and absorption of nutrients from the gut. The solubility of DF powders improves with more branching of polysaccharides, the presence of ionic groups such as pectin methoxylation, and the inter unit positional bonding such as β-glucans with mixed β−1-3 and β−1-4 linkages [11].

Ref. [81] investigated the effect of superfine grinding on some properties of defatted millet bran powder. They report a reduced particle size and surface roughness while an increase in the tap density, peak temperature, and angles of repose values after superfine grinding compared to coarse and fine powders [82] used turmeric residue powder in durum wheat pasta at different concentrations. They state overall sensory scores for the pasta samples added from 3 to 6% powde were acceptable [83]. added dried pineapple peel powder to cracker formulation.

The collective evidence from current literature highlights that the physicochemical and techno-functional performance of DF powders in food systems is predominantly governed by three interrelated parameters: the soluble-to-insoluble fibre ratio, the particle morphology (size, porosity, and surface chemistry), and the processing-induced matrix interactions [84, 85].

Despite significant advancements, several knowledge gaps limit the translation of DF powder research into standardized industrial applications. First, there is a lack of uniformity in experimental design and reporting, with many studies omitting key details such as particle size distribution, surface area, porosity, and specific mechanical energy input. Establishing a standardized analytical framework for evaluating DF powder characteristics—including hydration, swelling, emulsification, and flow properties—would enable more meaningful cross-study comparisons. Second, while numerous reports demonstrate functional improvements, quantitative structure–function correlations remain underexplored. Few studies systematically relate microstructural features (e.g., pore size, surface roughness) to techno-functional outcomes across different food matrices [86, 87].

Application of dietary fibre powders in food formulations

The food industry applies the use of DF powders in food formulations as an approach to improving the functional qualities and nutritional composition of various food ítems. Table 5 shows the different applications of dietary fibre powders in food formulations. According to recent meta-analyses, soluble fibres like psyllium and β-glucans are associated with reduced LDL cholesterol and improved glycaemic responses, while insoluble fractions such as wheat bran primarily reduce constipation risk [88, 89]. Evidence for additional outcomes, such as weight loss or metabolic syndrome prevention, remains mixed. Researchers classify DF as either soluble or insoluble. When combined with water, soluble fibre can dissolve and transform into a gel-like material, but insoluble fibre cannot dissolve but increases feces volume. Powdered DFs are processed ingredients of natural DFs that are obtained from diverse plant sources. Producers frequently isolate and concentrate DFs in fruits, vegetables, cereals, and other plant elements to create these powders. Producers also blend the DF powders into various food items for a longer shelf life [90]. DF powders can influence the mouthfeel and texture of foods by assisting in the achievement of an acceptable quality, moisture retention, and binding properties, depending on the type and quantity of fibre incorporated. Fibre powders, for example, can enhance the softness and structure of the crumb in baked items. Besides, DF powders are essential components in gluten-free and plant-based nutritional compositions because they are frequently inherently gluten-free and appropriate for vegan diets. They can improve the texture and structure of gluten-free goods and act as efficient alternatives for gluten substances [39, 91, 92]. Enhancing the nutrition of processed meals is one of the main uses for DF powders. The fibre content of foods like bread, pasta, cereals, snacks, and drinks may be greatly increased by adding these powders. As a result, the items become healthier for the digestive system and have an improved overall nutritional profile. Moreover, numerous positive health effects result from DF in the diet. For instance, soluble fibre has the potential to aid those with diabetes or those at risk of heart disease by stabilizing blood sugar levels and lowering cholesterol. Constipation and the promotion of regular bowel motions are both benefited by insoluble fibre [93, 94].

Although DF addition can improve nutritional quality, excessive inclusion levels often lead to undesirable effects on color, taste, and mouthfeel [95]. Comprehensive dose–response and sensory analyses remain scarce, making it difficult to define optimal incorporation levels for specific applications. Furthermore, while in vitro studies frequently suggest potential prebiotic or hypocholesterolemic benefits, in vivo and clinical validations of modified DF powders are still limited. The bioavailability, fermentation kinetics, and individual microbiome responses to specific DF types require further investigation, particularly in populations with metabolic or gastrointestinal disorders.

Dairy products

The physicochemical properties are significantly impacted by different levels of RS and inulin to low-fat cheddar cheese. By raising the RS and inulin content and the cheese hardness, the meltability and flowability were reduced. Inulin and RS were added to replace fat in low-fat cheese in the concentration of 0.5% and 1.0% to improve the sensory qualities [96]. Reconstituting skim milk with probiotic microbes significantly took less time to ferment when pineapple peel powder was added at 1%. Probiotic yoghurt with

Table 5 Applications of dietary fibre powders in foods formulations

Food Product	DF Source/Type	Concentration	Observed Impact	References
Cheddar cheese (low-fat)	Inulin, resistant starch	0.5–1%	↑ hardness, ↓ meltability and flowability, improved texture	[96]
Probiotic yoghurt	Pineapple peel powder	1%	↑ storage stability, reduced syneresis, softer texture	[97]
Probiotic ice cream	Coconut residue DF	0.02 g/mL	Softer texture, ↓ melting rate, ↑ protein, good probiotic survival	[98]
Ricotta cheese	Citrus DF	3–5%	↑ moisture, thicker texture, citrus flavor, best sensory balance at 3%	[100]
Chicken nuggets	Dragon fruit peel DF	~ 3% (powder form)	↑ protein, ↓ fat, improved antioxidant capacity, softer texture	[101]
Vienna sausages	Pineapple pomace DF	Variable (treated fibres)	↑ carotenoids, polyphenols, antioxidant capacity; ↓ nitrite and shrinkage	[102]
Chicken sausage	Sugarcane fibre	3% DF + 10% water	↑ cooking yield, ↑ antioxidant activity, no impact on consumer preference	[103]
Italian-style salami	Inulin, FOS, α-cyclodextrin	2%	Inulin/FOS improved redness, texture, sensory acceptance; α-cyclodextrin altered color	[104]
Frankfurters (phosphate-free)	Seaweed DF	1%	Improved texture, ↓ lipid oxidation, phosphate replacement effect	[106]
3D-printed snacks	Rye flour DF	Variable (with milk powder)	Improved firmness and stability, balanced expansion during baking	[107]
Cookies	Watermelon rind DF, hi-maize starch	20% DF or 30% starch	↑ DF, antioxidant activity, ↓ glycemic index (to medium/low)	[108]
Muffins	Kimchi by-product DF	1–4%	↑ hardness, ↓ volume/height; acceptable up to 2% DF	[110]
Bread	Soybean & chickpea DF	2% each	↑ phenolics, antioxidant activity; firmer crumb, slower staling	[112]
Bread	Rice bran DF (soluble 6%, insoluble 5%)	11% total	↑ texture, sensory score, shelf life	[113]

pineapple peel powder had a syneresis level equivalent to prebiotic inulin and increased storage periods. Nevertheless, the presence of pineapple peel powder dramatically reduced the hardness and storage modulus of both probiotic-treated and plain yoghurts [97]. The optimal strategy for probiotic (*Lactobacillus plantarum* ATCC 8014) ice cream production included 0.02 g/mL of coconut residue. This probiotic ice cream exhibited a soft texture, a low melting rate, a substantial amount of protein, a low-fat content, a probiotic-appropriate pH, and acceptable sensory evaluations for overall consumer satisfaction during 60 days of storage [98, 99]. Ricotta cheese added 5% citrus DF caused the fat content reduction, moisture content increased, and the higher yield of whey cheese. Ricotta cheese acquired a citrus flavor and aroma as its DF content increased, and its texture also thickened. The sample containing 3% DF from citrus provided the most well-balanced sensory results [100]. Ultrasonic carrot soluble DFs supplemented with yoghurt demonstrated greater stability. The yoghurt containing soluble DFs showed high structure stability, viscosity, consistency index, and pH. It also reduced flow index, titratable acidity, and syneresis percent [48].

Meat and poultry products

The influence of dragon fruit peel powder as an antioxidant DF on quality enhancement and sensitivity to lipid oxidation of chicken nuggets was evaluated during 20 days of chilled storage. Adding dragon fruit peel powder to nuggets increased protein, ash, and reduced fat content and improved emulsion stability and cooking yield while reducing pH. Additionally, the treated nuggets contained considerably more total phenolics and DF than the control. The addition of dragon fruit peel powder reduced the nuggets' hardness, gumminess, and chewiness while increasing their redness value [101]. DF concentrations were prepared from fresh and steamed under pressure pineapple pomace and then freeze-dry or hot air-dry to assess its combination effect with meats on the features of Vienna-type sausages. The maximum concentration of DF, carotenoids, polyphenols such as gallic, cinnamic, and p-coumaric acids, antioxidant capacity, and hydration characteristics were found in the sausages with pineapple DF. The higher ternary mixture of treated fibres had a decreasing influence on the amount of nitrites, moisture, shear force, and shrinkage in sausages while increasing the amount of carotenoids and antioxidant polyphenols [102]. With the addition of 3% sugarcane fibre and 10% water, the cooking yield of chicken sausage, total phenolic content, and radical scavenging activity significantly increased. Additionally, the addition of sugarcane fibre had no impact on the overall preference of consumers for chicken sausages [103]. The impact of a partial replacement of pork fat with inulin, fructooligosaccharides, and α-cyclodextrin on the physicochemical and sensory properties of low-fat Italian-style salami has been evaluated (Table 5). The addition of 2% of α-cyclodextrin enhanced lightness and decreased redness and yellowness. The sensory acceptability, textural characteristics, and redness were all enhanced by the addition of 2% inulin or fructooligosaccharides [104]. The addition of DF from red seaweed certainly improved the textural characteristics of phosphate-free frankfurters. Conversely, seaweed DF significantly inhibited the lipid oxidation of phosphate-free frankfurters during 21-day storage. Furthermore, it has been demonstrated that 1.00% seaweed DF provided the most optimal phosphates replacement effect and can most effectively improve the quality of phosphate-free frankfurter. In addition, the primary molecular interaction in phosphate-free frankfurters with seaweed DF added was hydrogen bond formation and hydrophobic forces [105, 106].

Bakery and snack products

Ref. [2] reviewed the effects of isolated and chemically modified DFs on baked products. Based on the previous research work, specific volume and crumb color are adversely affected in bakery products by adding DFs (i.e. β-glucans, arabinoxylans, cellulose, resistant starch, and pectin). Furthermore, according to [2], DFs improve gelling, thickening, and water binding properties in addition to increasing crumb hardness and water absorption and water retention. In addition, it was reported that DFs can function as a natural preservative by slowing down the staling process and increasing the shelf-life of baked goods.

A combination of milk powder and wholegrain rye flour demonstrated excellent potential as a formulation for high protein and DF snack foods prepared by extrusion-based 3D printing coupled with baking. Rye flour might be added to the recipe to mitigate the milk powder-based snack products considerable expansion during baking. Rye flour enhanced baking stability and firmness, whereas milk powder added volume and glossiness to the baked samples [107]. With the addition of increasing levels of either watermelon rind powder or hi-maize starch, the nutritional fibre content of the cookies was enhanced. The total phenolic content, radical scavenging activity, and ferric-reducing antioxidant power increased when the amount of watermelon rind powder in cookies increased (Table 5). The addition of up to 20% watermelon rind powder and 30% hi-maize starch in cookies facilitated a rise in DF, a decline in glycemic index to medium with watermelon rind powder and low with hi-maize starch, and an improvement in antioxidant activity [108]. In comparison to the control snack, the addition of *Wolffia globosa* freeze-dried powder enhanced crude protein, essential amino acids, and DF by 51%, 147%, and 83%, respectively. Besides, the functionality of snacks containing *Wolffia globosa* freeze-dried powder was all significantly improved, such as the total phenolic content, total flavonoid content, ferric ion reducing antioxidant power, and oxygen radical absorbance capacity [109]. In place of wheat flour, kimchi by-product powder from Chinese cabbage outer leaf containing 36.2% DF was used with 1%–4% DF content in baked muffins. Adding kimchi by-product powder reduced muffin height, volume, and chewiness but increased hardness. Up to the addition of 2% DF, there was no apparent difference in the overall acceptance of the muffins, and sensory evaluations likewise supported the excellent impact of the kimchi by-product powder [110]. Tea fibre was added to wheat flour and bread to elevate dough formation time significantly, water absorption, dough resisting deformation, configuration ratio, and dough softening and firmness while decreasing dough stability and flexibility, swelling power, baking durability, and loaf volume. The crumb properties of the tea fibre-treated bread were comparable to those of the control loaf. The sensory characteristics were the same between the control and treated bread containing 2.5% and 5.0% tea fibre [111]. When the white bread was prepared with 2% soybean and 2% chickpea DF, it was clear that phenolic compounds and antioxidant activities were significantly enhanced. Increasing DF caused white bread to stay firm during four days of storage and reduced weight loss of white bread [112]. The bread formulated with 6% soluble rice bran DF and 5% insoluble rice bran DF exhibited improved texture, specific volume, sensory evaluation, and shelf life of the bread [113].

Health effects associated with the consumption of fibre-enriched bread

The consumption of fibre-enriched bread has been widely associated with multiple health-promoting effects, owing to the physiological roles of both soluble and insoluble dietary fibres incorporated into cereal matrices. The enrichment of bread formulations with DF sources such as bran, fruit pomace, and legume husks can significantly enhance gut health, glycaemic regulation, lipid metabolism, and satiety [112, 113]. Soluble fibres such as β-glucans, pectins, and inulin form viscous gels in the gastrointestinal tract, thereby slowing glucose absorption and reducing postprandial glycaemic responses, which contribute to the prevention and management of type 2 diabetes [2]. Insoluble fibres from wheat bran, chickpea husk, and rice bran, on the other hand, increase fecal bulk and intestinal transit, facilitating detoxification and reducing constipation risk [22]. Moreover, fermentation of soluble fibres by gut microbiota leads to the production of short-chain fatty acids such as acetate, propionate, and butyrate, which are known to improve colonic health and reduce systemic inflammation [5, 6]. Regular intake of fibre-enriched bread has also been linked to improvements in blood lipid profiles, including lower total cholesterol and LDL levels, due to fibre-mediated bile acid sequestration and increased cholesterol excretion [11, 78]. Furthermore, DF incorporation enhances satiety and modulates appetite-regulating hormones, supporting weight management and reducing caloric intake in daily diets [88]. The synergistic combination of soluble and insoluble fibres in bread formulations, when optimized for particle size and hydration properties, can therefore promote gastrointestinal well-being, metabolic health, and cardiovascular protection without compromising sensory quality. Such fibre-enriched bakery products represent a practical and sustainable approach to increasing daily fibre intake and supporting long-term nutritional wellness [74, 112].

The effects of fibre addition on the sensory properties of fibre-enriched bread

The incorporation of dietary fibre (DF) into bread formulations can substantially influence sensory attributes such as appearance, color, texture, volume, aroma, and overall acceptability. These effects arise primarily from the water-binding capacity, particle size, and solubility of the added fibres, which interact with gluten and starch matrices during dough development and baking [2, 74]. Typically, fibre enrichment leads to increased dough firmness and decreased loaf volume due to gluten dilution and reduced gas retention, especially when high levels of insoluble fibre such as bran or legume husk are used [22, 112]. The colour of bread crumb and crust also tends to darken with the inclusion of cereal brans, fruit pomaces, or vegetable fibres, resulting from the presence of phenolic pigments and Maillard browning during baking [108, 110]. While these colour changes can sometimes reduce consumer appeal, moderate inclusion levels (typically 2–6%) are often acceptable and may even enhance the perception of wholegrain or natural products [113]. The mouthfeel and texture of fibre-enriched breads are closely related to the hydration properties and particle size of the incorporated fibre. Finer particle sizes improve smoothness and reduce the gritty sensation commonly associated with coarse fibres [42]. The use of soluble fibres such as β-glucans, inulin, or pectin can also improve crumb softness and moisture retention, counteracting the drying effect of insoluble fibres [114]. From a flavour standpoint, fibres derived from fruit by-products (e.g., apple, pineapple, or orange peel) may impart subtle fruity or acidic notes, whereas cereal brans can introduce a bitter or earthy aftertaste [39]. Sensory optimisation therefore requires balancing fibre concentration, type, and particle size to preserve desirable bread characteristics. Technological strategies such as enzymatic modification, micronization, or combining soluble and insoluble fractions have been shown to improve softness, cohesiveness, and overall consumer acceptability [42]. Overall, appropriate formulation and processing adjustments enable the development of fibre-enriched bread that meets nutritional goals while maintaining favorable sensory quality.

Technological challenges associated with the enrichment of fibre powder in food products

The incorporation of DF powder into food formulations presents several technological challenges that influence product quality, consumer acceptance, and processing behaviour. One of the main limitations is the undesirable effect of fibre enrichment on texture, sensory properties, and product structure. High fibre levels often increase dough hardness, reduce loaf volume, and negatively affect mouthfeel and color in bakery products due to water competition and dilution of gluten or protein matrices [2, 74]. Moreover, the hydrophilic nature of fibres interferes with water distribution and starch gelatinization, leading to denser structures and shorter shelf-life through accelerated staling [2]. Similarly, in dairy and meat analog products, the addition of insoluble fibres can cause phase separation, grittiness, or decreased emulsification stability [80, 106]. From a processing standpoint, the presence of coarse or irregular fibre particles alters dough rheology, extrusion flow, and spray drying performance due to poor dispersibility and agglomeration tendencies [77]. Another key challenge involves the unpleasant taste, color, or odor sometimes imparted by plant-derived fibres, particularly those from by-products rich in phenolic compounds or lignin [39].

To overcome these challenges, various modification and process-optimisation strategies have been proposed. Enzymatic treatments (e.g., cellulase, xylanase, or pectinase hydrolysis) can improve solubility and reduce particle size, leading to enhanced dispersibility and less gritty mouthfeel [32]. Mechanical treatments such as micronization, high-pressure homogenization, and ultrasound can disrupt fibrous aggregates and increase surface area, thereby improving water-binding and emulsion stability [43, 45]. Thermal or combined treatments (extrusion, steam explosion, or microwave-ultrasound coupling) can enhance hydration properties and modify sensory attributes while simultaneously reducing anti-nutritional components [56, 61]. Furthermore, the use of composite formulations (e.g., blending soluble and insoluble fibres, or combining fibres with proteins and hydrocolloids) has been shown to balance water retention and improve texture while maintaining nutritional value [91, 115]. Encapsulation or fine powder production through spray drying and freeze drying can also help mask undesirable sensory properties and enhance dispersibility [77]. Collectively, these approaches highlight the importance of tailoring both fibre source and processing method to achieve the desired structure–function–sensory equilibrium in fibre-enriched foods.

Regulatory issues and risk assessment

The definition and regulatory classification of dietary fibre (DF) continue to present significant challenges at both international and national levels. Historically, dietary fibre was regarded as a heterogeneous mixture of non-digestible carbohydrates and lignin resistant to hydrolysis by human digestive enzymes. However, the scope of the definition has evolved substantially with advancements in analytical techniques and physiological understanding. The Codex Alimentarius Commission [116] issued a harmonized definition that identifies DF as 'carbohydrate polymers with ten or more monomeric units that are not hydrolyzed by endogenous enzymes in the small intestine and belong to one of three categories: (1) edible carbohydrate polymers naturally occurring in foods; (2) those obtained from food raw materials by physical, enzymatic, or chemical means; and (3) synthetic carbohydrate polymers shown to have physiological benefits to health' [115]. Importantly, Codex allows national authorities to decide whether to include oligosaccharides with a degree of polymerization (DP) of 3–9 within the DF definition. This flexibility has led to differences in regulatory adoption across jurisdictions.

In the European Union, the European Food Safety Authority [117] recognizes DF as non-digestible carbohydrate polymers with three or more monomeric units that confer beneficial physiological effects such as laxation, cholesterol reduction, or modulation of postprandial glycaemia. The definitional differences create complexities for global manufacturers regarding nutrient labeling, compositional claims, and the recognition of modified or synthetic fibres. In some countries, oligosaccharides such as inulin, fructooligosaccharides (FOS), and galactooligosaccharides (GOS) are included within DF labelling systems, while in others they are categorized separately as prebiotics. Moreover, the lack of consensus on analytical methods—ranging from AOAC enzymatic–gravimetric assays to chromatographic approaches—further complicates cross-border equivalence of fibre content claims [13, 118].

Beyond definitional inconsistencies, regulatory acceptance of modified dietary fibres (e.g., carboxymethylated, hydroxypropylated, or enzymatically depolymerized fibres) remains uneven. While Codex allows inclusion of 'carbohydrate polymers obtained by physical, enzymatic, or chemical means,' national regulators often require proof of both non-digestibility and physiological efficacy before such fibres can be labeled as DF. Consequently, many emerging modified fibres, despite possessing improved techno-functional properties, cannot yet be marketed as 'dietary fibre' without additional substantiation. Harmonization of regulatory criteria is thus essential for supporting innovation and ensuring fair trade practices.

Future policy alignment should prioritize establishing standardized physiological efficacy endpoints (e.g., laxation, glycaemic attenuation, serum lipid reduction) and validated analytical reference methods that are applicable across different types of natural and modified fibres. Collaborative efforts between Codex, EFSA, FDA, and ISO bodies could facilitate the development of global guidance documents that integrate analytical reliability, safety assessment, and health claim substantiation. Moreover, risk assessments should encompass potential issues arising from chemical modifications (e.g., reagent residues, altered digestibility) and ensure that safety evaluations extend beyond compositional equivalence to include potential metabolic or microbiome effects. Greater international harmonization, transparent validation of physiological benefits, and consistent analytical frameworks are required to enable accurate labeling, consumer protection, and the sustainable commercialization of next-generation dietary fibre powders.

Conclusion and future perspectives

The synthesis of current research indicates that the structural and functional versatility of DF powders stems from their diverse botanical origins and the wide range of extraction, modification, and drying methods applied. The interplay between fibre composition, particle properties, and processing conditions determines the physicochemical and techno-functional performance of these powders in food matrices. Enzymatic and mechanical treatments have proven particularly effective in tailoring solubility, hydration, and interfacial properties, while combined hybrid approaches offer pathways to optimize both nutritional and sensory outcomes. Despite extensive progress, systematic correlations between structure, processing parameters, and functionality remain fragmented, limiting the translation of laboratory findings into scalable industrial applications.

Food developers can incorporate DF powders into formulations as versatile ingredients with numerous health benefits and technological advantages such as improving nutritional value, enhancing texture, and improving overall consumer satisfaction. DF powders have great potential as functional ingredients in food formulations, offering various health benefits and improving the texture, stability, and sensory properties of the final products. DF powders are technologically versatile ingredients that enhance texture and stability of foods. Clinically, meta-analyses support their role in lowering cholesterol, improving glycaemic control, and enhancing bowel function, though evidence for other benefits such as weight management is less consistent. The future of DF powders lies in continued exploration of novel sources, advanced processing techniques, and innovative formulations. Understanding individual responses to different types of fibre and addressing taste-related challenges will be essential for the sustained growth of this dynamic field. Despite their benefits, Incorporating DF powders poses challenges, including issues related to taste, palatability, and texture. From a practical perspective, techno-economic analyses, life cycle assessment (LCA), and environmental sustainability metrics are seldom integrated into DF processing research. These aspects are crucial for scaling up enzyme-assisted or hybrid technologies and ensuring alignment with clean-label and sustainable production goals. Additionally, powder engineering aspects such as flowability, cohesiveness, hygroscopicity, and segregation tendencies are underrepresented in current studies, despite their importance in manufacturing, handling, and reconstitution behaviour. Lastly, inconsistencies in international regulatory definitions of DF, particularly concerning oligosaccharides and chemically modified derivatives, continue to hinder product labeling and health claim standardization.

Future research should prioritize the establishment of method–matrix design models that quantitatively map processing parameters to powder microstructure and functional behaviour in specific food systems. Employing factorial design or response surface methodologies could facilitate prediction and optimisation of DF performance in food products. Hybrid or low-impact processing technologies, such as enzyme-assisted ultrasonication or mild extrusion coupled with fermentation, warrant further exploration as sustainable alternatives capable of maximizing both functionality and bioactivity while minimizing environmental impact. Additionally, future work should extend beyond compositional and functional characterisation toward engineering DF powders for improved manufacturability. Incorporating powder technology metrics such as bulk and tapped density, angle of repose, and blend uniformity into characterisation protocols will enhance control over formulation reproducibility and large-scale processing. Controlled chemical derivatization techniques (e.g., light carboxymethylation or hydroxypropylation) may be strategically employed to tailor viscosity or emulsification properties within regulatory limits. Microbial fermentation remains a promising area for future innovation, as it can simultaneously enhance solubility, introduce bioactive metabolites, and create porous structures that improve hydration and adsorption characteristics. Further comparative analyses between enzymatic, microbial, and hybrid processing routes will be essential to identify the most cost-effective and environmentally responsible solutions. Finally, advancing from in vitro digestion models to in vivo trials is essential for validating the physiological efficacy of DF powders in modulating glycaemic response, lipid metabolism, and gut microbiota composition. Establishing a unified data reporting template encompassing processing parameters, powder characteristics, application dose, and sensory and shelf-life outcomes will be invaluable for harmonizing research efforts and accelerating the translation of research findings into functional, consumer-acceptable food products.

Author contributions E.E., C.C.L., and I.H.T. wrote the main manuscript text. E.E. prepared figures. E.E. and C.C.L. prepared tables. EE rewieved and made necessary amendments.

Funding No funding was received for conducting this study.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Clinical trial number Not applicable.

References

1. AACC (2001) The definition of dietary fiber: report of the dietary fiber definition committee to the board of directors of the American association of cereal chemists. Cereal Foods World 46:112–123
2. Sempio R, Sahin AW, Walter J et al (2024) Impact of isolated and chemically modified dietary fiber on bakery products: current knowledge and future directions. Cereal Chem 101:7–37. https://doi.org/10.1002/cche.10722
3. Dhingra D, Michael M, Rajput H, Patil RT (2012) Dietary fibre in foods: a review. J Food Sci Technol 49:255–266. https://doi.org/10.1007/s13197-011-0365-5
4. Elleuch M, Bedigian D, Roiseux O et al (2011) Dietary fibre and fibre-rich by-products of food processing: characterisation, technological functionality and commercial applications: a review. Food Chem 124:411–421. https://doi.org/10.1016/j.foodchem.2010.06.077
5. Abdi R, Joye IJ (2021) Prebiotic potential of cereal components. Foods 10:2338. https://doi.org/10.3390/foods10102338
6. Barber TM, Kabisch S, Pfeiffer AFH, Weickert MO (2020) The health benefits of dietary fibre. Nutrients 12:3209. https://doi.org/10.3390/nu12103209
7. Román-Ochoa Y, M. Cantu-Jungles T, Choque Delgado GT et al (2024) Specific dietary fibers prevent heavy metal disruption of the human gut microbiota in vitro. Food Res Int 176:113858. https://doi.org/10.1016/j.foodres.2023.113858
8. Brown L, Rosner B, Willett WW, Sacks FM (1999) Cholesterol-lowering effects of dietary fiber: a meta-analysis. Am J Clin Nutr 69:30–42. https://doi.org/10.1093/ajcn/69.1.30
9. Anderson JW, Baird P, Davis RH Jr et al (2009) Health benefits of dietary fiber. Nutr Rev 67:188–205. https://doi.org/10.1111/j.1753-4887.2009.00189.x
10. Topping DL, Clifton PM (2001) Short-chain fatty acids and human colonic function: roles of resistant starch and nonstarch polysaccharides. Physiol Rev 81:1031–1064. https://doi.org/10.1152/physrev.2001.81.3.1031
11. Guillon F, Champ M (2000) Structural and physical properties of dietary fibres, and consequences of processing on human physiology. Food Res Int 33:233–245. https://doi.org/10.1016/S0963-9969(00)00038-7
12. Wang S, Fang Y, Xu Y et al (2022) The effects of different extraction methods on physicochemical, functional and physiological properties of soluble and insoluble dietary fiber from *Rubus chingii*Hu. fruits. J Funct Foods 93:105081. https://doi.org/10.1016/j.jff.2022.105081
13. Torbica A, Radosavljević M, Belović M et al (2022) Overview of nature, frequency and technological role of dietary fibre from cereals and pseudocereals from grain to bread. Carbohydr Polym 290:119470. https://doi.org/10.1016/j.carbpol.2022.119470
14. Pastell H, Putkonen T, Rita H (2019) Dietary fibre in legumes, seeds, vegetables, fruits and mushrooms: comparing traditional and semi-automated filtration techniques. J Food Compos Anal 75:1–7. https://doi.org/10.1016/j.jfca.2018.09.011
15. Avci E, Akcicek A, Tekin Cakmak ZH et al (2024) Isolation of protein and fiber from hot pepper seed oil byproduct to enhance rheology, emulsion, and oxidative stability of low-fat salad dressing. ACS Omega 9:10243–10252. https://doi.org/10.1021/acsomega.3c07410
16. Pathania S, Kaur N (2022) Utilization of fruits and vegetable by-products for isolation of dietary fibres and its potential application as functional ingredients. Bioactive Carbohydr Diet Fibre 27:100295. https://doi.org/10.1016/j.bcdf.2021.100295
17. Chen L, Wu Y, Jiang X et al (2023) Dietary fiber extraction from citrus peel pomace: yield optimization and evaluation of its functionality, rheological behavior, and microstructure properties. J Food Sci 88:3507–3523. https://doi.org/10.1111/1750-3841.16702
18. Chutia H, Sharma M, Das MJ, Mahanta CL (2024) Properties of dietary fibre from passion fruit seed obtained through individual and combined alkaline and ultrasonication extraction techniques. Waste Biomass Valorization 15:2345–2359. https://doi.org/10.1007/s12649-023-02288-0
19. Tunçil YE (2020) Dietary fibre profiles of Turkish Tombul hazelnut (Corylus Avellana L.) and hazelnut skin. Food Chem 316:126338. https://doi.org/10.1016/j.foodchem.2020.126338
20. Bhatt S, Gupta M (2023) Dietary fiber from fruit waste as a potential source of metabolites in maintenance of gut milieu during ulcerative colitis: a comprehensive review. Food Res Int 164:112329. https://doi.org/10.1016/j.foodres.2022.112329
21. Khorasaniha R, Olof H, Voisin A et al (2023) Diversity of fibers in common foods: key to advancing dietary research. Food Hydrocolloids 139:108495. https://doi.org/10.1016/j.foodhyd.2023.108495
22. Saini P, Islam M, Das R et al (2023) Wheat bran as potential source of dietary fiber: prospects and challenges. J Food Compos Anal 116:105030. https://doi.org/10.1016/j.jfca.2022.105030
23. Dai F-J, Chau C-F (2017) Classification and regulatory perspectives of dietary fiber. J Food Drug Anal 25:37–42. https://doi.org/10.1016/j.jfda.2016.09.006
24. Theuwissen E, Mensink RP (2008) Water-soluble dietary fibers and cardiovascular disease. Physiol Behav 94:285–292. https://doi.org/10.1016/j.physbeh.2008.01.001
25. Arslan A, Haros CM, Yalçın E, Güneş A (2021) Wet milling of buckwheat cultivars and some quality properties of the fractions. Food Sci Technol Int 28:320–330. https://doi.org/10.1177/10820132211011303
26. Tang C, Wu L, Zhang F et al (2022) Comparison of different extraction methods on the physicochemical, structural properties, and in vitro hypoglycemic activity of bamboo shoot dietary fibers. Food Chem 386:132642. https://doi.org/10.1016/j.foodchem.2022.132642
27. Li B, Akram M, Al-Zuhair S et al (2020) Subcritical water extraction of phenolics, antioxidants and dietary fibres from waste date pits. J Environ Chem Eng 8:104490. https://doi.org/10.1016/j.jece.2020.104490
28. Zhao S, Pan Z, Azarakhsh N et al (2024) Effects of high-pressure processing on the physicochemical and adsorption properties, structural characteristics, and dietary fiber content of kelp (Laminaria japonica). Curr Res Food Sci 8:100671. https://doi.org/10.1016/j.crfs.2023.100671
29. Perez-Pirotto C, Cozzano S, Hernando I, Arcia P (2023) Different green extraction technologies for soluble dietary fibre extraction from orange by-product. Int J Food Sci Technol 58:2042–2049. https://doi.org/10.1111/ijfs.15756
30. Maphosa Y, Jideani VA (2015) Dietary fiber extraction for human nutrition—A review. Food Rev Int 32:98–115. https://doi.org/10.1080/87559129.2015.1057840
31. Galanakis CM (2019) Dietary Fiber: Properties, Recovery and Applications. In: Dietary Fiber: Properties, Recovery, and Applications. Elsevier, pp ix–x
32. Gu M, Fang H, Gao Y et al (2020) Characterization of enzymatic modified soluble dietary fiber from tomato peels with high release of lycopene. Food Hydrocoll 99:105321. https://doi.org/10.1016/j.foodhyd.2019.105321
33. Zhao J, Xie W, Chen Z et al (2025) Enhancement of Dough Processing and Steamed Bread Quality with Modified Soybean Residue Dietary Fiber. Foods 14:346. https://doi.org/10.3390/foods14030346
34. Praveen MA, Parvathy KRK, Balasubramanian P, Jayabalan R (2019) An overview of extraction and purification techniques of

seaweed dietary fibers for immunomodulation on gut microbiota. Trends in Food Science & Technology 92:46–64. https://doi.org/10.1016/j.tifs.2019.08.011

35. Wagner CE, Ganjyal GM (2024) Impact of functional dietary fiber incorporation on the appearance and mechanical properties of extruded high moisture meat analogs. J Food Sci 89:4953–4968. https://doi.org/10.1111/1750-3841.17164
36. Stanišić N, Kurćubić VS, Stajić SB et al (2025) Integration of Dietary Fibre for Health Benefits, Improved Structure, and Nutritional Value of Meat Products and Plant-Based Meat Alternatives. Foods 14:2090. https://doi.org/10.3390/foods14122090
37. Zhao Q, Cheng D-Q, Tao M et al (2019) Rapid magnetic solid-phase extraction based on alendronate sodium grafted mesoporous magnetic nanoparticle for the determination of trans-resveratrol in peanut oils. Food Chem 279:187–193. https://doi.org/10.1016/j.foodchem.2018.12.014}
38. Verspreet J, Damen B, Broekaert WF et al (2016) A critical look at prebiotics within the dietary fiber concept. Annu Rev Food Sci Technol 7:167–190. https://doi.org/10.1146/annurev-food-081315-032749
39. Garcia-Amezquita LE, Tejada-Ortigoza V, Campanella OH, Welti-Chanes J (2018) Influence of drying method on the composition, physicochemical properties, and prebiotic potential of dietary fibre concentrates from fruit peels. J Food Qual 2018:1–11. https://doi.org/10.1155/2018/9105237
40. Gan J, Xie L, Peng G et al (2021) Systematic review on modification methods of dietary fiber. Food Hydrocolloids 119:106872. https://doi.org/10.1016/j.foodhyd.2021.106872
41. Aktas-Akyildiz E, Mattila O, Sozer N et al (2017) Effect of steam explosion on enzymatic hydrolysis and baking quality of wheat bran. J Cereal Sci 78:25–32. https://doi.org/10.1016/j.jcs.2017.06.011
42. Ma Q, Ma Z, Wang W et al (2022) The effects of enzymatic modification on the functional ingredient - Dietary fiber extracted from potato residue. LWT 153:112511. https://doi.org/10.1016/j.lwt.2021.112511
43. Bender ABB, Speroni CS, Moro KIB et al (2020) Effects of micronization on dietary fiber composition, physicochemical properties, phenolic compounds, and antioxidant capacity of grape pomace and its dietary fiber concentrate. LWT 117:108652. https://doi.org/10.1016/j.lwt.2019.108652
44. Abdol Rahim Yassin Z, Binte Abdul Halim FN, Taheri A et al (2023) Effects of microwave, ultrasound, and high-pressure homogenization on the physicochemical properties of sugarcane fibre and its application in white bread. LWT 184:115008. https://doi.org/10.1016/j.lwt.2023.115008
45. Wang F, Zeng J, Tian X et al (2022) Effect of ultrafine grinding technology combined with high-pressure, microwave and high-temperature cooking technology on the physicochemical properties of bean dregs. LWT 154:112810. https://doi.org/10.1016/j.lwt.2021.112810
46. He K, Zhang X, Li Y et al (2020) Water-insoluble dietary-fibers from *Flammulina velutiper* used as edible stabilizers for oil-in-water Pickering emulsions. Food Hydrocoll 101:105519. https://doi.org/10.1016/j.foodhyd.2019.105519
47. Kalla-Bertholdt A-M, Nguyen P-V, Baier AK, Rauh C (2021) Influence of dietary fiber on *in-vitro* lipid digestion of emulsions prepared with high-intensity ultrasound. Innov Food Sci Emerg Technol 73:102799. https://doi.org/10.1016/j.ifset.2021.102799
48. Zhang F, Yi W, Cao J et al (2019) Microstructure characteristics of tea seed dietary fibre and its effect on cholesterol, glucose and nitrite ion adsorption capacities *in vitro*: a comparison study among different modifications. Int J Food Sci Technol 55:1781–1791. https://doi.org/10.1111/ijfs.14465
49. Dong R, Liao W, Xie J et al (2022) Enrichment of yogurt with carrot soluble dietary fiber prepared by three physical modified treatments: microstructure, rheology and storage stability. Innov Food Sci Emerg Technol 75:102901. https://doi.org/10.1016/j.ifset.2021.102901
50. Yoshida BY, Prudencio SH (2020) Alkaline hydrogen peroxide improves physical, chemical, and techno-functional properties of okara. Food Chem 323:126776. https://doi.org/10.1016/j.foodchem.2020.126776
51. Li CL, Yu SY, Lu Y (2019) Study on extraction of dietary fiber from potato Peel by Acid-base chemical method. IOP Conf Ser Earth Environ Sci 267:52028. https://doi.org/10.1088/1755-1315/267/5/052028
52. Zhang W, Zeng G, Pan Y et al (2017) Properties of soluble dietary fiber-polysaccharide from papaya peel obtained through alkaline or ultrasound-assisted alkaline extraction. Carbohydr Polym 172:102–112. https://doi.org/10.1016/j.carbpol.2017.05.030
53. Kanwar P, Yadav RB, Yadav BS (2023) Cross-linking, carboxymethylation and hydroxypropylation treatment to sorghum dietary fiber: effect on physicochemical, micro structural and thermal properties. Int J Biol Macromol 233:123638. https://doi.org/10.1016/j.ijbiomac.2023.123638
54. Lee CC, Tomas M, Jafari SM (2020) Optical analysis of nanoencapsulated food ingredients by color measurement. Characterization of Nanoencapsulated Food Ingredients. Elsevier, pp 505–528
55. Lee KY, Park KH, Ahn J-B, Lee HG (2014) Effect of different chemical modification on the physicochemical properties of fiber-enriched polysaccharides isolated from wholegrain rice and buckwheat. Food Sci Biotechnol 23:1469–1475. https://doi.org/10.1007/s10068-014-0201-6
56. Zhang Y, Qi J, Zeng W et al (2020) Properties of dietary fiber from citrus obtained through alkaline hydrogen peroxide treatment and homogenization treatment. Food Chem 311:125873. https://doi.org/10.1016/j.foodchem.2019.125873
57. Gan J, Huang Z, Yu Q et al (2020) Microwave assisted extraction with three modifications on structural and functional properties of soluble dietary fibers from grapefruit peel. Food Hydrocolloids 101:105549. https://doi.org/10.1016/j.foodhyd.2019.105549
58. Wang K, Li M, Wang Y et al (2021) Effects of extraction methods on the structural characteristics and functional properties of dietary fiber extracted from kiwifruit (*Actinidia deliciosa*). Food Hydrocolloids 110:106162. https://doi.org/10.1016/j.foodhyd.2020.106162
59. Zheng Y, Li Y, Tian H (2020) Effects of carboxymethylation, acidic treatment, hydroxypropylation and heating combined with enzymatic hydrolysis on structural and physicochemical properties of palm kernel expeller dietary fiber. LWT 133:109909. https://doi.org/10.1016/j.lwt.2020.109909
60. Qiao C-C, Zeng F-K, Wu N-N, Tan B (2021) Functional, physicochemical and structural properties of soluble dietary fiber from rice bran with extrusion cooking treatment. Food Hydrocolloids 121:107057. https://doi.org/10.1016/j.foodhyd.2021.107057
61. Schmid V, Steck J, Mayer-Miebach E et al (2021) Extrusion processing of pure chokeberry (*Aronia melanocarpa*) pomace: impact on dietary fiber profile and bioactive compounds. Foods 10:518. https://doi.org/10.3390/foods10030518
62. Zhai X, Ao H, Liu W et al (2021) Physicochemical and structural properties of dietary fiber from Rosa Roxburghii pomace by steam explosion. J Food Sci Technol 59:2381–2391. https://doi.org/10.1007/s13197-021-05254-7
63. Ma C, Ni L, Guo Z et al (2022) Principle and application of steam explosion technology in modification of food fiber. Foods 11:3370. https://doi.org/10.3390/foods11213370
64. Chen J, Huang H, Chen Y et al (2020) Effects of fermentation on the structural characteristics and in vitro binding capacity of soluble dietary fiber from tea residues. LWT 131:109818. https://doi.org/10.1016/j.lwt.2020.109818

65. Sun C, Wu X, Chen X et al (2020) Production and characterization of okara dietary fiber produced by fermentation with *Monascus anka*. Food Chem 316:126243. https://doi.org/10.1016/j.foodchem.2020.126243
66. Lee C-C, Chen J, Frank JF (2016) Influence of extracellular cellulose and Colanic acid production on the survival of Shiga Toxin–Producing *Escherichia coli* on spinach and lettuce after Chlorine treatment. J Food Prot 79:666–671. https://doi.org/10.4315/0362-028x.jfp-15-375
67. Chu J, Zhao H, Lu Z et al (2019) Improved physicochemical and functional properties of dietary fiber from millet bran fermented by *Bacillus natto*. Food Chem 294:79–86. https://doi.org/10.1016/j.foodchem.2019.05.035
68. Hu Y-B, Wang Z, Xu S-Y (2008) Treatment of corn bran dietary fiber with xylanase increases its ability to bind bile salts, in vitro. Food Chem 106:113–121. https://doi.org/10.1016/j.foodchem.2007.05.054
69. Wei C, Ge Y, Liu D et al (2022) Effects of high-temperature, high-pressure, and ultrasonic treatment on the physicochemical properties and structure of soluble dietary fibers of millet bran. Front Nutr. https://doi.org/10.3389/fnut.2021.820715
70. Su D, Zhu X-D, Wang Y et al (2021) Impact of high-pressure homogenization on the microstructure and rheological properties of citrus fiber. Int J Food Eng 17:299–308. https://doi.org/10.1515/ijfe-2020-0206
71. Wang C, Lin M, Li Y, Guo Z (2024) Improvement of soluble dietary fiber quality in *Tremella fuciformis* stem by steam explosion technology: an evaluation of structure and function. Food Chem 437:137867. https://doi.org/10.1016/j.foodchem.2023.137867
72. Luo M, Wang C, Wang C et al (2023) Effect of alkaline hydrogen peroxide assisted with two modification methods on the physicochemical, structural and functional properties of bagasse insoluble dietary fiber. Front Nutr. https://doi.org/10.3389/fnut.2022.1110706
73. Wu L, Tang C, Chen L, Zhao J (2023) Modified dietary fiber from soybean dregs by fermentation alleviated constipation in mice. Food Chemistry: X 19:100810. https://doi.org/10.1016/j.fochx.2023.100810
74. Ermiş E (2021) Food powders properties and characterization. Springer International Publishing, Cham
75. Foschia M, Peressini D, Sensidoni A, Brennan CS (2013) The effects of dietary fibre addition on the quality of common cereal products. J Cereal Sci 58:216–227. https://doi.org/10.1016/j.jcs.2013.05.010
76. van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84:523–538. https://doi.org/10.1007/s11192-009-0146-3
77. Raghavendra SN, Rastogi NK, Raghavarao KSMS, Tharanathan RN (2004) Dietary fiber from coconut residue: effects of different treatments and particle size on the hydration properties. Eur Food Res Technol 218:563–567. https://doi.org/10.1007/s00217-004-0889-2
78. George S, Thomas A, Kumar MVP et al (2023) Impact of processing parameters on the quality attributes of spray-dried powders: a review. Eur Food Res Technol 249:241–257. https://doi.org/10.1007/s00217-022-04170-0
79. Lecumberri E, Goya L, Mateos R et al (2007) A diet rich in dietary fiber from cocoa improves lipid profile and reduces malondialdehyde in hypercholesterolemic rats. Nutrition 23:332–341. https://doi.org/10.1016/j.nut.2007.01.013
80. Lu Y, Zhang L, Schutyser MAI (2023) Linking particle morphology and functionality of colloid-milled dietary fibre concentrates from various plant sources. LWT 186:115206. https://doi.org/10.1016/j.lwt.2023.115206
81. Tolve R, Zanoni M, Ferrentino G et al (2024) Dietary fibers effects on physical, thermal, and sensory properties of low-fat ice cream. LWT 199:116094. https://doi.org/10.1016/j.lwt.2024.116094
82. Liang K, Liang S, Zhu H (2024) The physicochemical characteristics and phenolic bioaccessibility of defatted millet bran powder prepared using superfine grinding. LWT 201:116173. https://doi.org/10.1016/j.lwt.2024.116173
83. Long DQ, Doan TBN, Ton NMN et al (2024) Quality of durum wheat pasta fortified with different ratios of turmeric residue powder. J Agric Food Res 16:101220. https://doi.org/10.1016/j.jafr.2024.101220
84. Mala T, Piayura S, Itthivadhanapong P (2024) Characterization of dried pineapple (*Ananas comosus* L.) peel powder and its application as a novel functional food ingredient in cracker product. Future Foods 9:100322. https://doi.org/10.1016/j.fufo.2024.100322
85. Nevara GA, Muhammad SKS, Zawawi N et al (2021) Dietary fiber: fractionation, characterization and potential sources from defatted oilseeds. Foods 10:754. https://doi.org/10.3390/foods10040754
86. Kalla-Bertholdt A-M, Baier AK, Rauh C (2023) Potential of modification of techno-functional properties and structural characteristics of Citrus, Apple, Oat, and pea dietary fiber by High-Intensity ultrasound. Foods 12:3663. https://doi.org/10.3390/foods12193663
87. Poutanen KS, Fiszman S, Marsaux CFM et al (2018) Recommendations for characterization and reporting of dietary fibers in nutrition research. Am J Clin Nutr 108:437–444. https://doi.org/10.1093/ajcn/nqy095
88. Feng X, Yu B, Regenstein JM, Wang L (2023) Effect of particle size on composition, physicochemical, functional, and structural properties of insoluble dietary fiber concentrate from citrus Peel. Food Sci Technol Int 29:195–203. https://doi.org/10.1177/10820132211063973
89. Verstegen REM, Kostadinova AI, Merenciana Z et al (2021) Dietary fibers: effects, underlying mechanisms and possible role in allergic asthma management. Nutrients 13:4153. https://doi.org/10.3390/nu13114153
90. Salvatore S, Battigaglia MS, Murone E et al (2023) Dietary fibers in healthy children and in pediatric Gastrointestinal disorders: a practical guide. Nutrients 15:2208. https://doi.org/10.3390/nu15092208
91. Ermis E, Tekiner IH, Lee CC et al (2023) An overview of protein powders and their use in food formulations. J Food Process Eng. https://doi.org/10.1111/jfpe.14326
92. Das AK, Nanda PK, Madane P et al (2020) A comprehensive review on antioxidant dietary fibre enriched meat-based functional foods. Trends Food Sci Technol 99:323–336. https://doi.org/10.1016/j.tifs.2020.03.010
93. Bahrami A, Delshadi R, Cacciotti I et al (2022) Targeting foodborne pathogens via surface-functionalized nano-antimicrobials. Adv Colloid Interface Sci 302:102622. https://doi.org/10.1016/j.cis.2022.102622
94. Yang Y, Ma S, Wang X, Zheng X (2017) Modification and application of dietary fiber in foods. J Chem 2017:1–8. https://doi.org/10.1155/2017/9340427
95. Demirci M, Lee C-C, Çavuş M, Çağlar MY (2020) Oleogels for food applications. Biopolymer-Based Formulations. Elsevier, pp 781–811
96. Chakraborty P, Witt T, Harris D et al (2019) Texture and mouthfeel perceptions of a model beverage system containing soluble and insoluble oat bran fibres. Food Res Int 120:62–72. https://doi.org/10.1016/j.foodres.2019.01.070
97. Murtaza MS, Sameen A, Rafique S et al (2023) Impact of dietary fiber (Inulin and resistant Starch) on the quality parameters of low

fat cheddar cheese from Buffalo milk. Pak J Zool 55. https://doi.org/10.17582/journal.pjz/20200630120620
98. Sah BNP, Vasiljevic T, McKechnie S, Donkor ON (2016) Physicochemical, textural and rheological properties of probiotic yogurt fortified with fibre-rich pineapple peel powder during refrigerated storage. LWT-Food Sci Technol 65:978–986. https://doi.org/10.1016/j.lwt.2015.09.027
99. Hanafi FNA, Kamaruding NA, Shaharuddin S (2022) Influence of coconut residue dietary fiber on physicochemical, probiotic (*Lactobacillus plantarum* ATCC 8014) survivability and sensory attributes of probiotic ice cream. LWT 154:112725. https://doi.org/10.1016/j.lwt.2021.112725
100. Pourjafar H, Jafari SM, Ansari F et al (2023) The role of probiotics in improving food safety: inactivation of pathogens and biological toxins. Curr Pharm Biotechnol 24. https://doi.org/10.2174/1389201024666230601141627
101. Zinina O, Khitsenko A, Neverova O et al (2021) Research of the Ricotta made from cheese Whey enriched with citrus dietary fiber. IOP Conf Ser Earth Environ Sci 699:12006. https://doi.org/10.1088/1755-1315/699/1/012006
102. Madane P, Das AK, Nanda PK et al (2019) Dragon fruit (*Hylocereus undatus*) peel as antioxidant dietary fibre on quality and lipid oxidation of chicken nuggets. J Food Sci Technol 57:1449–1461. https://doi.org/10.1007/s13197-019-04180-z
103. Montalvo-González E, Aguilar-Hernández G, Hernández-Cázares AS et al (2018) Production, chemical, physical and technological properties of antioxidant dietary fiber from pineapple pomace and effect as ingredient in sausages. CyTA-J Food 16:831–839. https://doi.org/10.1080/19476337.2018.1465125
104. Fang Z, Lin P, Ha M, Warner RD (2018) Effects of incorporation of sugarcane fibre on the physicochemical and sensory properties of chicken sausage. Int J Food Sci Technol 54:1036–1044. https://doi.org/10.1111/ijfs.13894
105. Bis-Souza CV, Ozaki MM, Vidal VAS et al (2019) Can dietary fiber improve the technological characteristics and sensory acceptance of low-fat Italian type salami? J Food Sci Technol 57:1003–1012. https://doi.org/10.1007/s13197-019-04133-6
106. Cofrades S, Benedí J, Garcimartin A et al (2017) A comprehensive approach to formulation of seaweed-enriched meat products: from technological development to assessment of healthy properties. Food Res Int 99:1084–1094. https://doi.org/10.1016/j.foodres.2016.06.029
107. Yuan D, Xu Y, Kong B et al (2023) Application of seaweed dietary fiber as a potential alternative to phosphates in frankfurters with healthier profiles. Meat Sci 196:109044. https://doi.org/10.1016/j.meatsci.2022.109044
108. Lille M, Kortekangas A, Heiniö RL, Sozer N (2020) Structural and textural characteristics of 3D-printed protein- and dietary fibre-rich snacks made of milk powder and wholegrain rye flour. Foods. https://doi.org/10.3390/foods9111527
109. Naknaen P, Itthisoponkul T, Sondee A, Angsombat N (2016) Utilization of watermelon rind waste as a potential source of dietary fiber to improve health promoting properties and reduce glycemic index for cookie making. Food Sci Biotechnol 25:415–424. https://doi.org/10.1007/s10068-016-0057-z
110. On-Nom N, Promdang P, Inthachat W et al (2023) *Wolffia globosa*-based nutritious snack formulation with high protein and dietary fiber contents. Foods 12:2647. https://doi.org/10.3390/foods12142647
111. Heo Y, Kim M, Lee J, Moon B (2019) Muffins enriched with dietary fiber from Kimchi by-product: baking properties, physical–chemical properties, and consumer acceptance. Food Sci Nutr 7:1778–1785. https://doi.org/10.1002/fsn3.1020
112. Arı Akın P, Tayfun KE, Tamer U, Boyacı İH (2021) Use of tea fibers as a source of dietary fiber in wheat flour and bread. Cereal Chem 98:1049–1058. https://doi.org/10.1002/cche.10444
113. Niño-Medina G, Muy-Rangel D, de la Garza A et al (2019) Dietary fiber from Chickpea (Cicer arietinum) and soybean (Glycine max) husk byproducts as baking additives: functional and nutritional properties. Molecules 24:991. https://doi.org/10.3390/molecules24050991
114. Ouyang K, Tao Q, Xie H et al (2024) Enrichment of bread with soluble and insoluble rice bran dietary fibers: a comparative study. J Cereal Sci 117:103927. https://doi.org/10.1016/j.jcs.2024.103927
115. Lille M, Kortekangas A, Heiniö R-L, Sozer N (2020) Structural and textural characteristics of 3D-printed protein- and dietary fibre-rich snacks made of milk powder and wholegrain rye flour. Foods 9:1527. https://doi.org/10.3390/foods9111527
116. Codex Alimentarius Commission (CAC) (2009) ALINORM 09/32/26: Report of the 30th Session of the Codex Committee on Nutrition and Foods for Special Dietary Uses. Rome
117. EFSA NDA Panel (2010) Scientific opinion on dietary reference values for carbohydrates and dietary fibre. EFSA J 8:1462
118. AACC (2009) AACC international approved methods. AACC international approved methods
119. Bai X, Huang L, He Y (2025) Visualising and analysing the research trends of dietary fiber: a bibliometric study. Discover Applied Sciences 7:467. https://doi.org/10.1007/s42452-025-06969-4
120. Haskey N, Gold SL, Faith JJ, Raman M (2023) To fiber or not to fiber: the swinging pendulum of fiber supplementation in patients with inflammatory bowel disease. Nutrients 15:1080. https://doi.org/10.3390/nu15051080
121. Hu L, Guo J, Zhu X et al (2020) Effect of steam explosion on nutritional composition and antioxidative activities of okra seed and its application in gluten-free cookies. Food Sci Nutr 8:4409–4421. https://doi.org/10.1002/fsn3.1739
122. Wang YQ, Wang J-D, Cai Z-H et al (2022) Improved physicochemical and functional properties of dietary fiber from *Rosa roxburghii* pomace fermented by *Bacillus natto*. Food Biosci 50:102030. https://doi.org/10.1016/j.fbio.2022.102030
123. Xiao Z, Yang X, Zhao W et al (2022) Physicochemical properties of insoluble dietary fiber from pomelo (*Citrus grandis*) Peel modified by ball milling. J Food Process Preserv 46. https://doi.org/10.1111/jfpp.16242
124. Zhang M-Y, Liao A-M, Thakur K et al (2019) Modification of wheat bran insoluble dietary fiber with carboxymethylation, complex enzymatic hydrolysis and ultrafine comminution. Food Chem 297:124983. https://doi.org/10.1016/j.foodchem.2019.124983
125. Liao A-M, Zhang J, Yang Z-L et al (2022) Structural, physicochemical, and functional properties of wheat bran insoluble dietary fiber modified with probiotic fermentation. Front Nutr. https://doi.org/10.3389/fnut.2022.803440
126. Cui J, Gu X, Zhang Q et al (2015) Production and anti-diabetic activity of soluble dietary fiber from apricot pulp by *Trichoderma viride* fermentation. Food Funct 6:1635–1642. https://doi.org/10.1039/C5FO00207A
127. Afoakwah NA (2022) Jerusalem artichoke (*Helianthus tuberoses*) dietary-fiber powder functionality. Heliyon 8:e12426. https://doi.org/10.1016/j.heliyon.2022.e12426
128. Feng Y, Zhu J, Li Y, Cheng Z (2024) Effects of grinding methods of Tartary buckwheat leaf powder on the characteristics and micromorphology of wheat dough. Foods 13:1233. https://doi.org/10.3390/foods13081233
129. Zhu Y, Zhou X, Zhang Y et al (2024) Impacts of superfine grinding on structural characteristics and lipid-lowering effect of bitter melon polysaccharides. Int J Food Sci Technol 59:3813–3822. https://doi.org/10.1111/ijfs.17124
130. Wang J, Zhang X, Li S et al (2024) Steam explosion-assisted grinding improves the functional properties and antioxidant

activity of Java tea-leaf powders. J Sci Food Agric. https://doi.org/10.1002/jsfa.13627

131. Jakha KH, Goyal C, Dhyani P et al (2024) Characterization of Langra Mango Peel Powder and assessment of its prebiotic and antioxidant potential. J Food Biochem 2024:1–17. https://doi.org/10.1155/2024/9026617
132. Ngo HBG, Phu ML, Tran TTT et al (2024) Dietary fiber-and antioxidant-enriched cookies prepared by using jackfruit rind powder and ascorbic acid. Heliyon 10:e30884. https://doi.org/10.1016/j.heliyon.2024.e30884
133. Mall UP, Patel VH (2024) Carrot pomace powder: a promising source of polyphenols and prebiotics for improving gut health. Nutrire 49:9. https://doi.org/10.1186/s41110-023-00250-7