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A review of innovative approaches for valorizing brewing by-products for food applications and consumer perceptions

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The brewing industry generates a large amount of solid by-products, including spent grain, yeast, and hops, which present environmental challenges but offer opportunities for valorization in food applications. These solid by-products are rich in dietary fiber, proteins, polyphenols, and bioactive compounds with potential health benefits. This review explores innovative strategies for upcycling brewing solid by-products into functional food ingredients, focusing on advanced extraction techniques, biotechnological processes, novel food formulations, and food packaging. We highlight green extraction methods, enzymatic hydrolysis, and microbial fermentation as key approaches for enhancing bioavailability, functionality, and sensory properties. Furthermore, consumer perception plays a crucial role in the successful market acceptance of food products valorized from brewing solid by-products. Factors such as sensory attributes, sustainability awareness, and transparent communication influence consumer acceptance and willingness to purchase. Despite advancements in extraction, bioprocessing, and product development, challenges remain in optimizing processing technologies, ensuring food safety, and increasing consumer engagement. This review provides a comprehensive perspective on bridging technological advancements with market-driven approaches to support sustainable and circular food systems.

Sustainability spotlight

The brewing industry generates millions of tonnes of nutrient-rich side streams annually, most of which are underutilized or disposed of, contributing to environmental burdens. This review emphasizes the valorization of brewing side streams through green extraction methods, enzymatic hydrolysis, and microbial fermentation to enhance the bioavailability, functionality, and sensory properties of recovered compounds. Beyond technological innovation, consumer perception is important for successful market adoption, with sensory quality, sustainability awareness, and transparent communication determining acceptance and purchase decisions. By transforming low-value side streams into nutritionally enriched products, the work advances sustainable food systems, promotes resource efficiency, and addresses consumer demand for eco-friendly solutions. The sustainable advancement aligns strongly with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 2 (Zero hunger), SDG 3 (Good health and well-being), and SDG 12 (Responsible consumption and production).

1. Introduction

The global beer industry, valued at approximately US$ 101.22 billion in 2024, is projected to grow at an annual rate of 2.67% between 2025 and 2034.[1] However, this growth raises increasing concerns about sustainability and the circular economy due to the industry's substantial environmental footprint. The production of 1 L of beer typically requires 2.5–6 L of water, 4–10 g of yeast, 8–200 g of malted grain, and 0.5–2 g of hop, in addition to 0.123 kW of electricity, 11.1 MJ of thermal energy, and 0.04 kg of fossil fuels. This process also results in the generation of significant waste streams, including 100–250 g of spent grain (SG), 15–40 g of spent yeast (SY), 1–5 g of spent hop (SH) and trub, and 1.5–5 L of wastewater per 1 L of beer produced, with an associated carbon footprint of 760–1900 g CO_2 equivalent.[2–4] Given the scale of global beer production, which was approximately 200 million metric tonnes in 2023, the industry produces substantial quantities of waste. In 2021, brewing resulted in 37.8 million tonnes of SG, 4.8 million tonnes of SY, 2.6 million tonnes of SH, and 5.7–189 billion hectoliters of wastewater.[5] These figures underscore the urgent need for sustainable practices and innovative valorization strategies to reduce waste and enhance resource efficiency in beer production.

SG is the predominant brewing by-product (BBP), accounting for approximately 85% of the total solid BBPs, and is therefore a primary target for valorization in food applications.

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Nutritionally, SG is rich in dietary fiber, primarily β-glucan and arabinoxylan (19–70%), and proteins (15–32%), along with smaller amounts of B-vitamins, minerals, and phenolic compounds.[6] Despite its abundance and nutritional composition, only 5–10% of SG has been explored for use in food products. The majority is still used as low-value animal feed (around 70%) or disposed of in landfills (approximately 20%) across European countries.[5] SY constitutes 10–15% of total solid BBPs and is mainly composed of *Saccharomyces cerevisiae* or *Saccharomyces pastorianus*, depending on the beer type.[7] Although yeast is commonly reused through repitching to inoculate new fermentation batches, its viability declines over successive cycles, eventually affecting beer quality and leading to disposal.[3] Like SG, SY is nutritionally valuable, containing 15–78% protein (rich in essential amino acids such as glutamic acid, histidine, alanine, and aspartic acid), 3–36% fiber (mainly β-glucan), B-vitamins, and minerals such as potassium, magnesium, and sodium.[6] SH, although representing only about 5% of solid BBPs by volume, contains the highest protein content among solid BBPs (up to 70% of dry mass) as well as significant concentrations of phenolic compounds. Notably, around 85% of the compounds in hops (the most expensive ingredients in brewing) are lost during processing and ended up as SH.[5] Collectively, the compositional profiles of SG, SY, and SH highlight their considerable potential for valorization in the food industry, particularly in the development of functional ingredients, nutritional fortification strategies, sustainable food products, and active packaging solutions.

Over the past two decades, the valorization of BBPs for food applications has been the subject of extensive research, as evidenced by numerous comprehensive reviews.[3,5,7,8] However, several persistent challenges continue to obstruct the effective integration of BBPs into food systems. One major limitation is their high moisture content,[7] which renders them highly perishable and complicates both storage and transportation. Additionally, the transformation of BBPs into food-grade ingredients frequently necessitates the use of advanced and costly processing technologies, particularly at industrial scales, thereby increasing the cost of the final products. Although consumer demand for sustainable and functional foods is rising, awareness and acceptance of ingredients derived from BBPs remain limited. Concerns about potential contamination or undesirable compounds also persist due to the origin of these materials. Additionally, incorporating BBPs into food formulations can adversely affect sensory properties such as texture, flavor, and appearance, which may be unfamiliar or unappealing to consumers.[9] While the existing literature has thoroughly explored the general valorization of BBPs, significant gaps remain concerning the application of innovative processing technologies aimed at enhancing their functionality in food systems. Furthermore, research examining consumer perceptions of BBP-based food products is still limited, which is an important aspect for facilitating successful product development and market acceptance.

In this review, we highlighted the functional components derived from BBPs and their potential applications in food systems. It further explores recent innovations in extraction and processing technologies designed to enhance the functionality of these components. In addition, the review provides a comprehensive overview of recent advancements in the valorization of BBPs for incorporation into food products and packaging materials. Special emphasis is placed on consumer perception, acceptance, and the market viability of BBP-based food innovations. By integrating technical developments with consumer and market-oriented perspectives, this review seeks to address existing gaps in the literature. It thereby contributes to the advancement of sustainable and economically viable strategies for the utilization of BBPs within the food sector.

2. Functional components from brewing by-products

The compositional profiles of SG, SY, and SH are illustrated in Fig. 1. SG is primarily composed of insoluble dietary fibers and proteins, making up nearly half and up to 30% of its dry weight, respectively.[10] Among the fiber constituents, arabinoxylan is the most abundant, and has been associated with prebiotic activity, glycemic control, and antioxidant effects.[11] The protein fraction of SG is notable for its high content of essential amino acids, which account for approximately 38% of total protein, with lysine being particularly abundant. This profile positions SG as a promising alternative to traditional plant-based protein sources such as cereals and legumes.[12–15] However, the limited solubility of SG proteins restricts their direct use in food applications. Enzymatic hydrolysis has been shown to improve their solubility, enhance bioactivity (*e.g.*, anti-inflammatory and anti-bacterial properties), and confer favorable techno-functional attributes such as emulsification and foaming capacity, thereby expanding their applicability in food systems.[16,17] In addition, SG contains 7–10% lipids, primarily composed of essential fatty acids such as linoleic and oleic acids, which together constitute more than 50% of total lipid content. The presence of phytosterols further enhances its nutritional value, as these compounds have been linked to cholesterol-lowering effects and cardiovascular benefits.[18,19] SG is also a rich source of phenolic acids, both bound and free, including ferulic and *p*-coumaric acids, which are recognized for their antioxidant and anti-inflammatory activities.[20] Moreover, essential micronutrients such as calcium, magnesium, and B-vitamins contribute to its overall nutritional profile. Nevertheless, the dense lignocellulosic matrix of SG presents a barrier to the bioavailability and extraction of these functional components, often necessitating pre-treatment strategies to improve accessibility and functionality.

SY is a nutritionally rich by-product, offering a high-quality protein content comparable to soy, with essential amino acids comprising approximately 40% of its total protein, which is sufficient to meet the FAO's daily intake recommendations.[21] Its carbohydrate fraction predominantly consists of β-glucans (50–60%), mannoproteins (35–40%), glycogen (1–23%), and chitin (1–3%). β-Glucans function as dietary fibers with health-promoting effects, while mannoproteins contribute to desirable techno-functional properties such as emulsification and

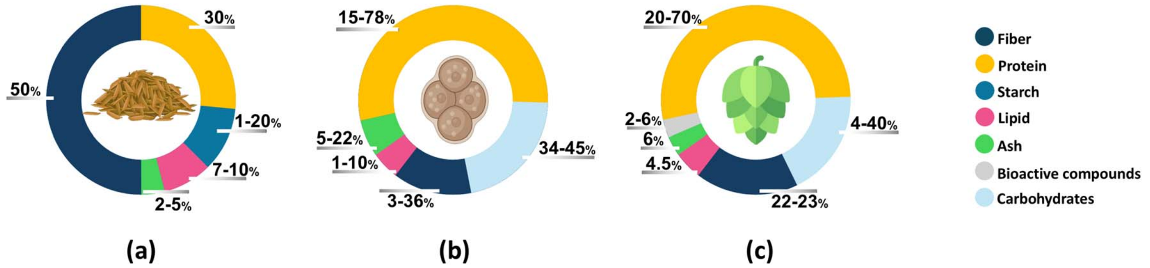

Fig. 1 Proximate composition (%) of brewing by-products including (a): SG, (b): SY and (c): SH.

thickening.[22] SY has a low lipid content (<10% dry weight), dominated by neutral lipids (~58%), including acylglycerols, sterols, steryl esters, and free fatty acids.[5] Among these, squalene accounts for roughly 33% of the total lipid fraction, positioning SY as a promising source for nutraceutical and cosmetic applications. SY also contains B-vitamins, essential minerals, and phenolic compounds, including gallic acid, catechin, and hydroxycinnamic acids, which impart antioxidant and antimicrobial activities.[23] Residual hop-derived constituents, such as α- and β-acids and volatile essential oils, may also be retained in SY during the brewing process.[24] Despite its high nucleic acid content (6–15%) limiting direct intake due to health risks like hyperuricemia,[25] SY holds promise for use in functional foods.

SH is a concentrated source of residual hop-derived compounds, including polyphenols (*e.g.*, xanthohumol and catechins), essential oils, and bitter acids (α- and β-acids), which exhibit anti-microbial, anti-inflammatory, and antioxidant properties.[26–28] SH also contains substantial amounts of protein (up to 70% of dry weight), dietary fiber, and lipids.[5] However, its pronounced bitterness presents a sensory challenge for direct incorporation into food products without prior modification. The presence of bioactive terpenes and prenylated flavonoids further enhances its potential for use in functional foods and as a natural preservative. Additionally, hot trub, often co-processed with SH, contributes supplementary protein and fermentable sugars, increasing its applicability as a fermentation substrate.

3. Advanced processing strategies for the valorization of brewing by-products

The valorization of BBPs increasingly relies on advanced green extraction and biotechnological methods to recover bioactive compounds, proteins, lipids, and fibers while enhancing their functional properties. Green extraction technologies, including subcritical water extraction, deep eutectic solvents, supercritical fluid extraction, and ultrasound- or microwave-assisted extraction, have demonstrated improved efficiency, sustainability, and cost-effectiveness. Meanwhile, microbial fermentation, enzymatic hydrolysis, and solid-state fermentation have been shown to improve their digestibility, bioavailability, and functionality. Table 1 summarizes these methods, highlighting their applications, advantages, and limitations. In addition, Table 2 summarizes recent studies employing advanced strategies for BBP valorization, highlighting the targeted functional ingredients, and the main findings.

3.1. Green extraction methods

3.1.1. Subcritical water extraction. Subcritical water extraction is an advanced green technology that uses pressurized hot water (100–374 °C) as a tunable solvent to extract bioactive compounds, proteins, and dietary fibers from BBPs. Unlike conventional solvent-based methods (*e.g.*, Soxhlet extraction), it takes advantage of water's altered physicochemical properties at subcritical conditions, such as reduced polarity, increased diffusivity, and enhanced solubility of both hydrophobic and hydrophilic compounds.[29–31] Under subcritical conditions, the dielectric constant of water decreases, allowing it to act like an organic solvent, dissolving medium-polarity bioactive compounds such as phenolics, flavonoids, proteins, and polysaccharides. This transformation also facilitates the hydrolysis of lignocellulosic matrices in SG and SH, breaking down complex carbohydrates into bioavailable fermentable sugars and soluble fibers. The elevated temperature in subcritical water extraction increases mass transfer rates, enhancing the diffusion of intracellular bioactive compounds and reducing processing time compared to conventional methods.[31,32]

The efficiency of this extraction process depends on temperature, pressure, residence time, and water-to-material ratio. It was found that temperatures between 180–250 °C maximized polyphenol extraction, while excessive temperatures (>270 °C) caused thermal degradation of bioactive compounds. High-pressure (>100 bar) enhanced the selective recovery of bioactive peptides from SG proteins and prevented Maillard reactions that could lead to the formation of undesired compounds.[30,32,33] The subcritical water extraction of SG at the pilot scale (170 °C, 22 min) resulted in the release of 56% of total carbohydrates, with a 78% pentose yield, of which 18% were monomers and 82% were oligomers. The process produced 6.5 g peptides per L (64% protein recovery), 21 mg free amino acids/g protein (2.17% yield), and a total phenolic content of 17.84 mg of gallic acid equivalents (GAE) per gram of dry SG. The presence of degradation inhibitors, such as furfural (0.22 g L^{-1}), acetic acid (0.31 g L^{-1}), and formic acid (0.13 g L^{-1}), was relatively low. Scaling up from the lab to the pilot scale demonstrated good reproducibility, particularly for arabinoxylo-oligomers, gluco-oligomers, protein yield, and free amino acid release, although xylo-oligomer yield was 13%

Table 1 Green extraction and biotechnological treatments potentially applied to valorize BBPs highlight their functional roles, key advantages, and limitations

Treatments	Applications for valorizing BBPs	Advantages	Disadvantages	References
Subcritical water extraction	• Extracts polyphenols, proteins, fibers, and sugars • Increases recovery of ferulic acid, catechins, and flavonoids • Breaks down lignocellulose • Improves protein solubility and digestibility	• High efficiency and eco-friendly • Bioactive compound preservation • Tunable selectivity • Shorter processing time compared t● conventional methods	• Possible degradation of bioactive compounds at high temperatures • Requirement for optimized pressure t● achieve high efficiency • Need for further optimization of scalability and energy effectiveness	32, 35 and 29
Deep eutectic solvents	• Extracts phenolic acids, flavonoids, and proteins • Enhances antioxidant activity and fiber content • Improves protein solubility and bioactive retention • Enables selective extraction of target compounds	• Sustainable and low toxicity • Efficient for polyphenols and proteins • Adaptable and compatible with a wide range of bioactive compounds	• High viscosity • Limited scalability • Challenges in solvent recovery	29 and 52
Supercritical fluid extraction	• Recovers lipophilic bioactive compounds • Enhances oxidative stability • Produces high-purity extracts	• Solvent-free • Highly selective • High purity of bioactive extracts • Reduced oxidation during extraction	• Energy-intensive • High-pressure equipment requirement • High initial cost which limits industrial application	40 and 43
Ultrasound- and microwave-assisted extraction	• Extracts phenolics, proteins, and antioxidants • Improves bioactive recovery with minimal solvents	• Fast, efficient, and less solvent use • Preservation of bioactive compounds and antioxidant activity • High extraction yields	• Efficiency influenced by solvent type, ultrasound intensity, and microwave power • Possible bioactive compound degradation at high powers • Scalability challenges	45, 47 and 44
Microbial fermentation	• Enhances protein digestibility and fiber solubility • Produces bioactive compounds for gut health • Improves probiotic stability in functional dairy and fermented products • Increases short-chain fatty acid production	• Improvement of bioavailability and production of bioactive compounds • Cost-effective and scalable • Reduced bitterness and improved sensory properties	• Requirement for optimized fermentation conditions • Contamination risk • Inconsistent product quality depending on microbial strain	49 and 51
Enzymatic treatments	• Hydrolyzes proteins and carbohydrates • Converts residual starches into fermentable sugars for microbial fermentation • Enhances the antioxidant activity of released peptides and polyphenols	• High selectivity in extraction • Improvement of functional properties • Efficient extraction of proteins and fibers • Synergistic action with microbial fermentation	• High cost of enzymes • Efficiency dependent on substrate composition • Requirement for precise pH and temperature control	35 and 60

Table 1 (*Contd.*)

Treatments	Applications for valorizing BBPs	Advantages	Disadvantages	References
Solid-state fermentation	• Enhances proteins digestibility • Improves aroma and texture • Modifies sensory properties	• Low energy consumption • Increased protein and bioactive content • Sustainable food production	• Requirement of strict fungal strain control • Scalability challenges • Longer fermentation time compared to submerged fermentation	64 and 59

higher at the lab scale. Additionally, the residual solid showed a decrease in hemicellulose and an increase in glucan content, improving digestibility for potential enzymatic glucose release.[34]

The application of subcritical water extraction for extracting polyphenols and flavonoids from BBPs demonstrated a significant increase in total phenolic content and antioxidant activity compared to conventional solvent extraction. Subcritical water extraction at 170 °C yielded 24 mg GAE per g dry SG extract, a significantly higher phenolic content than that obtained *via* Soxhlet extraction. It was also found that subcritical water extraction resulted in high recovery rates of ferulic acid, *p*-coumaric acid, and catechins, with ferulic acid reaching maximum extraction efficiency at 180 °C, while higher temperatures (>250 °C) caused degradation.[29,31,32] Subcritical water-extracted phenolic compounds from SG exhibited strong antioxidant and anti-bacterial activities, achieving an 80% inhibition rate against *L. innocua* and 60% against *E. coli.*[32,35] These findings highlight the potential of subcritical water extraction as an effective green extraction method for enhancing the value of BBPs in food and nutraceutical applications.

3.1.2. Deep eutectic solvents. Deep eutectic solvents have emerged as highly tunable solvents for extracting bioactive compounds, proteins, and fibers from BBPs. Unlike conventional organic solvents, they consist of a eutectic mixture of hydrogen bond donors and acceptors, forming stable liquid phases that enhance the solubilization of functional molecules.[36] Their effectiveness in BBPs valorization is attributed to their ability to disrupt lignocellulosic structures, facilitating the release of bound bioactive compounds. Choline chloride-based deep eutectic solvents, particularly those formulated with organic acids like lactic, citric, or malic acid, showed high efficiency in extracting ferulic acid, *p*-coumaric acid, and hydroxycinnamic acids from SG.[37] Additionally, deep eutectic solvent extraction of SH demonstrated superior efficiency in isolating hop-derived bioactive compounds such as xanthohumol, humulones, and lupulones.[38] Recent studies show that deep eutectic solvent formulations with urea and choline chloride enhanced SG protein solubility and digestibility by disrupting hydrogen bonds and exposing hydrophobic residues, while also improving emulsification, foaming capacity, and gelation properties.[39,40] Deep eutectic solvents were also applied in the fractionation of SG, with a focus on lignin recovery and biomass valorization. The process began with hot water pretreatment in an autoclave, yielding a 25% soluble fraction rich in sugars for microbial fermentation, while the insoluble fraction underwent treatment with deep eutectic solvents for lignin extraction. The solvents effectively isolated and modified lignin, enhancing its purity and potential for biopolymer applications.[41]

Thermodynamic and rheological studies highlight the role of viscosity of deep eutectic solvents in extraction efficiency. Lower viscosity formulations (*e.g.*, choline chloride-lactic acid) promoted faster solute diffusion, while more viscous ones (*e.g.*, glycerol-based) stabilized compounds, preventing oxidation and degradation.[36] Deep eutectic solvents can form stable complexes with polyphenols and proteins, enhancing their thermal and oxidative stability. Recent studies showed that combining deep eutectic solvents with ultrasound or microwave techniques improved polyphenol and protein recovery from SG and SH and reduced solvent consumption.[39,40]

3.1.3. Supercritical fluid extraction. Supercritical fluid extraction uses supercritical fluids, primarily carbon dioxide at temperatures and pressures above their critical point (*e.g.*, 31.1 °C and 73.8 bar for CO_2), exhibiting both liquid-like solvating power and gas-like diffusivity. This unique physicochemical behavior allows efficient solubilization of lipophilic bioactive compounds while preserving thermally sensitive molecules.[40] The adjustability of supercritical fluid parameters allows for selective fractionation of different classes of bioactive compounds by fine-tuning pressure, temperature, and co-solvent composition, making supercritical fluid extraction a superior alternative to conventional solvent-based extractions such as Soxhlet extraction and maceration.[30,35]

Supercritical fluid extraction was proven particularly effective in recovering bioactive compounds, including α-acids, β-acids, and volatile essential oils from SH.[40,42] Moreover, it was applied to extract lipid-soluble antioxidants such as tocopherols, sterols, and carotenoids from SY. The process was particularly effective for extracting lipid-soluble vitamins, sterols, and polyunsaturated fatty acids, particularly omega-3 and omega-6 fatty acids.[30,40,43] Optimal extraction occurs at pressures of 200–400 bar and temperatures of 40–60 °C, which maximize bioactive compound yield while preventing thermal degradation. Pressures above 250 bar and moderate temperatures (∼50 °C) further increase unsaturated fatty acid yield from SY. Additionally, supercritical fluid extraction effectively recovered hydrophobic peptides from SY and SH. Higher pressures

Table 2 Summary of studies on the application of advanced approaches for BBP valorization

BBPs	Treatments and their conditions	Target compounds/product	Key results	References
SG & SH	Subcritical water extraction (pilot scale): 170–190 °C, 20–25 min	Polyphenols, proteins, carbohydrates	• Phenolic content up to 24 mg GAE per g • 56% carbohydrate release • 64% protein recovery	34
SG	Subcritical water extraction (pilot scale, 170 °C, 22 min)	Carbohydrates, peptides, phenolics	• Total carbohydrates released: 56%; pentoses: 78% (18% monomers, 82% oligomers); peptides: 6.5 g L^{-1} (64% protein yield) • Total phenolic content: 17.8 mg GAE per g dry BSG	34
SG	Subcritical water (defatted SG, 170 °C) & H_2O_2 bleaching	Phenolics, cellulose fractions	• Extracts: 24 mg GAE per g phenolics, antioxidant activity (71 mg/mg dry biomass DPPH), anti-bacterial (*E. coli* inhibited at 140 mg mL^{-1}) • Cellulose fraction: 20–25% yield, 42–71% purity	32
SY	Supercritical CO_2 extraction	Yeast-derived metabolites	• Improved efficiency—extracts rich in flavor-enhancing esters, phenolics, and peptides • Distinctive and desirable flavor profiles in beverages	43
SG	Enzymatic hydrolysis (feruloyl esterase) with ultrasound pretreatment, optimized pH 5.3, 60 °C, 22 h	Ferulic acid, antioxidants	• Released 1.06 mg ferulic acid per g	62
SG	Deep eutectic solvent (DES)-mediated fractionation (choline chloride–based DES, with hot water pretreatment)	Sugars, lignin, cellulose-rich fraction	• Hot water: ~25% sugar solubilization • DES: 15–20% lignin recovery and cellulose-rich fraction	41
SG	Microbial proteolysis using *B. cereus*, *B. lentus*, *B. polymyxa*, *B. subtilis*	Protein hydrolysates with antioxidant activity	• Degree of hydrolysis: 43.1% (*B. cereus*), 41.8% (*B. lentus*) • Antioxidant activity (μM TEAC per g): 1621.3 (ABTS), 160.9 (DPPH), 284.1 (FRAP) for *B. cereus*	61
SG	Arabinoxylan extraction *via* simultaneous saccharification and fermentation, followed by concentration	Soluble arabinoxylan (AX)	• 21% solubilization • Concentrated fraction: ~99% soluble AX • 3.5-fold increase in bifidobacteria (*in vitro*)	70
SG	Solid-state fermentation with *A. ibericus*	Carbohydrase-rich enzymatic extract	• More than 45% of pentose released (*in vitro*) • Improved *in vivo* digestibility of dry matter, starch, cellulose, glucans, and energy in European seabass diets	58
SG	Solid-state fermentation with *B. subtilis* WX-17	Nutritionally enriched SG (amino acids, fatty acids, antioxidants)	• Total amino acids: 2-fold increase (0.859 → 1.894 mg g^{-1} SG) • Unsaturated fatty acids: 1.7-fold increase • Antioxidant activity: 5.8-fold increase *vs.* unfermented SG	71
SG	Symbiotic fermentation with *B. velezensis* and *L. brevis*	Nutritionally enriched SG (Gamma-aminobutyric acid, GABA)	• Total amino acids: +52.2%; glutamic acid: +155%; GABA: +144%; enhanced cellulase and protease activities	67
SY	Autolysis and enzymatic hydrolysis	Protein hydrolysates and peptides	• Released bioactive peptides with antioxidant activity and functional properties	54

also enhanced the solubilization of hop-derived terpenes and polyphenols, while lower temperatures were essential for preserving thermally unstable molecules such as tocopherols and sterols.[43] Adding ethanol (5–15%) as a co-solvent improved the solubility of polar compounds, expanding the range of extracted bioactive compounds, particularly polyphenols, flavonoids, and protein-bound bioactive compounds. Supercritical CO_2 with ethanol co-solvent was shown to be more effective than conventional extraction methods in fractionating hydroxycinnamic acids from SG.[40,43]

3.1.4. Ultrasound- and microwave-assisted extraction. Ultrasound- and microwave-assisted extraction are innovative and sustainable techniques for recovering bioactive compounds from BBPs. Ultrasound-assisted extraction employs high-frequency sound waves to create cavitation bubbles that disrupt cell walls and improve mass transfer, leading to greater extraction efficiency in a shorter time.[44] Meanwhile, microwave-assisted extraction uses microwave irradiation to rapidly heat solvents and break down plant cell structures, making it an energy-efficient method for extracting valuable bioactive compounds.[45]

Ultrasound-assisted extraction has been optimized to recover bioactive compounds such as ferulic acid, vanillic acid, and *p*-coumaric acid, which exhibit strong antioxidant and antimicrobial properties. It was found that ultrasound-assisted extraction at 80 °C for 50 min with an ethanol-to-water ratio of 65/35 significantly improved total phenolic content from SG, increasing yield by 156% compared to conventional extraction methods.[44] Ultrasound-assisted extraction effectively recovered bitter acids and xanthohumol from SH using ethyl acetate–methanol (1 : 1, v/v) and 80% methanol as solvents. The highest xanthohumol yield, reaching 43 μg mL^{-1}, was obtained after incubation with iron oxide nanoparticles for 48 h.[46] In contrast, microwave-assisted extraction achieved the most efficient extraction from SH in just one minute using ethanol, resulting in the highest antioxidant activity and free-radical scavenging capacity.[45]

Ultrasound-assisted extraction was explored for recovering phenolic compounds and bitter acids from hot trub. Optimization using 58% ethanol, a solid–liquid ratio of 1 g/32 mL, and a temperature of 36 °C for 30 min resulted in a total phenolic content of 7.23 mg GAE per g of trub.[47] The ultrasound treatment also enhanced antioxidant activity, with the highest levels measured after 5 min at 50% amplitude. For cell lysis and protein recovery from SY, ultrasound-assisted extraction was optimized to 70% amplitude for 7.5 min in pulsation mode, leading to an 85% increase in soluble protein release.[48]

3.2. Biotechnological treatments

3.2.1. Microbial fermentation. The role of microbial fermentation in enhancing the digestibility and bioavailability of proteins, fibers, and bioactive compounds in BBPs has gained significant attention in the last decade. This process involves the metabolic activity of bacteria, yeasts, and fungi, which break down complex carbohydrates, proteins, and polyphenols into more bioavailable forms. Fermentation not only enhances nutritional value but also improves sensory attributes, making BBPs suitable for functional food applications.[49,50] For example, lactic acid bacteria fermentation has been important in enhancing the prebiotic and health-promoting properties of BBPs. Lactic acid bacteria's fermentative metabolism produces lactic acid and short-chain fatty acids, which promote gut health by modulating the microbiota and improving nutrient bioavailability. The acidification during fermentation also lowers the pH, helping to prevent spoilage and inhibit the growth of pathogenic bacteria.[51] It was also found that arabinoxylans and β-glucans in SG served as fermentable substrates for beneficial bacteria such as *Bifidobacterium*, *Enterococcus*, and *Lactobacillus*, enhancing short-chain fatty acid production in livestock nutrition. These compounds enhance intestinal nutrient absorption, glucose metabolism, immune function, and lipid digestion while suppressing pathogens such as *Salmonella* and *E. coli*.[52,53]

Additionally, fermentation was shown to increase the solubility of dietary fibers, such as arabinoxylans and β-glucans, in SG and SY, while also enhancing phenolic acid bioavailability. The metabolic activity of bacteria was suggested to release bound polyphenols from the lignocellulosic matrix of SG.[54] The fermentation of SG with *Rhodosporidium toruloides* was investigated for microbial lipid production. Using pretreated SG hydrolysates as a substrate, the process yielded 18.5 g L^{-1} of cell dry weight and 10.41 g L^{-1} of lipids, corresponding to a lipid content of 56.45%. The lipid profile was comparable to that of vegetable oils. Lipid accumulation was significantly higher with pretreated SG hydrolysates than with synthetic glucose-xylose media. These findings demonstrate the potential of *R. toruloides* for valorizing SG into microbial lipids.[55]

Yeast fermentation, particularly using *S. cerevisiae*, has been explored for transforming SY into a source of bioactive peptides with antioxidant, anti-microbial, and anti-inflammatory properties. During fermentation, proteolytic enzymes released by yeast hydrolyze proteins into smaller peptides and free amino acids, many of which exhibit bioactive functions, such as radical scavenging and anti-hypertensive effects. Yeast fermentation also enhances the sensory characteristics of BBPs, particularly by reducing bitterness from residual hop-derived compounds in SG and SY.[56,57]

3.2.2. Enzymatic treatments. Enzymatic treatments use specific enzymes, such as cellulases, proteases, and amylases, to hydrolyze the structural components of BBPs, enhancing the release of fermentable sugars, amino acids, and bioactive compounds. Cellulases and proteases were studied for breaking down the proteins and complex lignocellulosic matrix of SG, increasing the availability of proteins, soluble fibers, and fermentable sugars.[58] Amylase treatments converted residual starches in SG and SY into fermentable sugars, essential for microbial fermentation, probiotic beverages, and bioethanol production.[59] Enzymatic hydrolysis also improves the digestibility and bioavailability of proteins in SY and SG, producing bioactive peptides.[23] For instance, protease-assisted hydrolysis released smaller peptides and free amino acids obtained from SG, enhancing emulsification and foaming properties.[60]

Enzymatic hydrolysis of SG with *Bacillus* strains produced antioxidant-rich protein hydrolysates, with *B. cereus* (43.06% degree of hydrolysis) and *B. lentus* (41.81%) exhibiting the highest proteolytic activity. The hydrolysates demonstrated strong antioxidant properties, with *B. cereus* achieving the highest values in the 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) assay (1621.31 mM Trolox eq. per g), the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay (160.93 mM Trolox eq. per g), and the ferric reducing antioxidant power (FRAP) assay (284.08 mM ferric reducing antioxidant power per gram). These findings confirm enzymatic hydrolysis as an effective approach for generating bioactive peptides for functional foods.[61] Enzymatic treatment of SG was further optimized for ferulic acid extraction, significantly improving recovery rates. Among various pretreatment methods, autoclaving increased ferulic acid yield by 23.7%. The most effective enzyme cocktail, Depol 740L, exhibited high feruloyl esterase activity (0.4 U mL^{-1}), enhancing synergy with cellulases and xylanases. Response surface methodology optimization revealed that the highest ferulic acid yield (1.06 ± 0.01 mg g^{-1} dry weight, 43.13% of the alkaline hydrolysis yield) occurred at pH 5.27, 60 °C, and 1.72% enzyme concentration. However, even under optimized conditions, 55% of ferulic acid remained inaccessible, highlighting the need for further process improvements.[62] The combination of multiple enzymes, such as cellulases and xylanases or proteases and carbohydrases, was also suggested to enhance extraction yield and improve overall bioactive functionality of SG, SH, and SY.[35] Enzyme efficiency depends on concentration, pH, temperature, and reaction time, with optimal conditions varying by enzyme: cellulases work best at pH 4.5–5.5 and 50–60 °C, proteases at pH 6.0–7.5 and 45–55 °C, and amylases at pH 5.0–6.0 and 55–65 °C.[35,60,63]

3.2.3. Solid-state fermentation. Solid-state fermentation is an innovative bioprocessing technique that utilizes filamentous fungi, particularly *Aspergillus* and *Rhizopus* species, as well as certain *Bacillus* species to enhance the nutritional and functional properties of BBPs. Unlike submerged fermentation, solid-state fermentation is carried out in the absence or near absence of free water, making it an energy-efficient and sustainable method for bioconversion. This process was investigated for protein enrichment, fiber modification, and bioactive compound enhancement in BBPs, contributing to their valorization in food and biotechnological applications.[54,64] For example, solid-state fermentation was reported to significantly improve protein enrichment in SG, increasing the bioavailability of essential amino acids and bioactive peptides.[65,66] In other study, solid-state fermentation of SG with *Bacillus velezensis* and *Levilactobacillus brevis* enhanced its nutritional quality by promoting microbial synergy, increasing cellulase and protease activities, and improving fiber and protein degradation. Consequently, soluble sugars increased by 78.5%, total amino acids by 52.2%, and γ-aminobutyric acid by 144.1%, demonstrating the effectiveness of co-fermentation for upgrading SG into a higher-value ingredient.[67]

Fungal metabolism can lead to the secretion of proteolytic enzymes, which break down protein complexes into smaller peptides and free amino acids, thereby enhancing their digestibility and absorption. Furthermore, fungal species such as *A. oryzae* and *R. oligosporus* improved the production of bioactive peptides with antioxidant, anti-hypertensive, and antimicrobial properties from SG.[65,68] Fungal metabolism also promoted the release of phenolic compounds, flavonoids, and β-glucans, which enhances antioxidant and immune-modulating activities. Additionally, fungal fermentation significantly improved mineral bioavailability, particularly magnesium, iron, and zinc, by reducing anti-nutritional factors such as phytic acid, thus improving the nutritional profile of solid-state fermentation-treated SG.[58,64,69]

4. Food applications of valorized brewing by-products

Valorized BBPs have been successfully incorporated into a wide range of food products, enhancing nutritional value, functional attributes, and sensory qualities. Both whole BBPs and their extractives have been applied in bakery goods, dairy formulations, functional powders, meat alternatives, beverages, food preservation systems, active packaging, and as substrates or media components in fermentation processes. Table 3 summarizes these diverse applications, outlining key functionalities and formulation challenges. In addition, Table 4 provides a summary of studies on the use of BBPs in various food applications.

4.1. Prebiotic source

SG and SY are increasingly recognized as valuable sources of prebiotic compounds, particularly oligosaccharides and β-glucans, which support gut microbiota modulation, metabolic health, and immune function.[71,72] Arabinoxylans, arabinoxylooligosaccharides, and xylooligosaccharides derived from SG selectively stimulate the growth of *Bifidobacterium* and *Lactobacillus*, enhancing short-chain fatty acid production. Similarly, β-1,3/1,6-glucans from SY act as prebiotics and immunomodulators, promoting a beneficial microbiota profile and improved immune response.[72–74] The prebiotic effects of SG-derived arabinoxylans and xylooligosaccharides vary with structure and fermentation behavior. An *in vitro* study found that arabinoxylans obtained through ultrasound-assisted extraction fermented rapidly, decreasing pH and increasing content of short-chain fatty acids, while those extracted using an alkaline method fermented more slowly, supporting gut microbiota in the distal colon.[75] Arabinoxylooligosaccharides and xylooligosaccharides obtained from SG exhibited a strong bifidogenic effect, increasing *Bifidobacterium* counts by 1.2–3.6 log-fold and demonstrating greater efficacy than commercial fructooligosaccharides. Cultures enriched with arabinoxylooligosaccharides also showed higher propionate production, indicating potential roles in cholesterol reduction and improved insulin sensitivity.[74]

SY-derived β-glucans further support beneficial microbiota (*e.g.*, *Bifidobacterium, Lactobacillus*) and suppress pathogens such as *Salmonella* and *E. coli.*[72] *In vivo* studies in pigs demonstrated that early-life β-glucan supplementation enhanced gut microbiota composition and immune response, increasing microbial diversity and favoring *Firmicutes* and *Bacteroidetes*. It also lowered gut pH, creating a more favorable environment for beneficial bacteria.[53] SG-derived oligosaccharides and SY β-glucans are ideal for food applications due to their stability and functional properties. They can be used in fermented dairy products, fiber-enriched snacks, fruit juices, plant-based milks, and sports drinks to promote gut health and immune function. SY β-glucans, with Generally Recognized As Safe status under

Table 3 Nutritional and technological advantages and challenges of incorporating BBPs into food products

Food applications	Functions	SG	SY	SH	References
Prebiotic source	Benefits	• Rich in arabinoxylans, arabinoxylooligosaccharides, xylooligosaccharides which support *Bifidobacterium* and *Lactobacillus* growth	• Contains bitter acids and polyphenols with antioxidant and antimicrobial effects	• Rich in proteins, polyphenols, and essential amino acids	73 and 74
		• Enhances short-chain fatty acid production, improving gut health	• Supports gut microbiota by inhibiting harmful bacteria	• Enhances fermentation stability and microbial balance	
		• Provides fiber, promoting gut motility and microbial diversity	• Contributes to intestinal barrier integrity	• Provides bioactive peptides with gut health benefits	
	Limitations	• High fiber content may cause dryness and bitterness in food	• Intense bitterness limits food applications	• High lipid and protein content complicates food use	
		• Requires processing to improve digestibility	• Gut microbiota interactions need further study	• Limited research on its gut microbiota effects	
Bakery and cereal-based products	Benefits	• Rich in fiber for bread, cookies, cakes, and gluten-free formulations	• Rich in β-glucans, enhancing dough elasticity and moisture retention	• Provides antioxidant properties that improve product stability	76, 103, 54 and 77
		• Enhances texture and nutritional value	• Extends shelf life and reduces staling in baked products		
		• Improves water absorption and dough hydration	• Supports gut health through prebiotic effects		
	Limitations	• Can lead to dryness at high concentrations	• May interfere with yeast activity if not properly processed	• Intense hop aroma and bitterness may restrict application	
		• May impart a bitter aftertaste due to polyphenols	• Can impart a strong yeast-like flavor at high concentrations		
Dairy products and fermented foods	Benefits	• Enhances fermentation and probiotic viability in yogurts and dairy beverages	• Enhances cheese texture and water retention	• Polyphenols enhance antioxidant stability	103 and 6
		• Provides dietary fiber and phenolic antioxidants	• Improves probiotic stability in fermented dairy drinks	• May have antimicrobial effects in fermented dairy	
			• Provides functional proteins and supports emulsification		
	Limitations	• Improper processing may lead to a grainy texture	• High concentrations may alter sensory properties	• Can impart strong bitter notes to dairy products	
			• Potential for off-flavors in dairy formulations		
Encapsulation strategies and functional food powder	Benefits	• Provides a natural fiber and protein matrix for microencapsulation	• Improves probiotic viability and retention due to β-glucans	• Hydrothermally processed proteins and lipids improve emulsification-based encapsulation	92, 93, 54 and 76
		• Improves oxidative stability of polyphenols and essential fatty acids	• Enhances heat-sensitive vitamin and antioxidant peptide stability	• Enhances bioactive retention for omega-3 fatty acids and anti-microbial compounds	
		• Supports controlled release of probiotics and antioxidants	• Supports co-encapsulation strategies for synbiotic formulations		
	Limitations	• May require additional processing to optimize solubility	• May introduce strong yeast-like flavors if not properly processed	• High lipid content may require stabilization to prevent oxidation	

Table 3 (*Contd.*)

Food applications	Functions	SG	SY	SH	References
Food preservation and active packaging	Benefits	• Rich in polyphenols, reducing lipid oxidation and improving food stability • Used in biodegradable packaging materials • Improves structural integrity of starch-based films	• Forms natural biofilms for fresh product preservation • Enhances microbial safety and moisture retention in packaging	• Acts as a natural anti-microbial agent in packaging • Inhibits bacterial and fungal growth in food storage	103 and 105
	Limitations	• Requires additional processing for extraction	• Limited solubility in certain formulations	• Can impart strong flavors if not carefully controlled	
Meat alternatives and processed meat products	Benefits	• Enhances texture and water-binding capacity in plant-based and processed meats • Increases fiber and protein content, improving nutritional value	• Used as a fat replacer, emulsifier, and moisture-retaining agent • Enhances umami flavor, reducing the need for artificial enhancers	• Natural preservative in processed meats • Reduces lipid oxidation and extends shelf-life	103, 106 and 6
	Limitations	• Can make formulations drier if not optimized	• Strong taste may require balancing in formulations	• May contribute to bitterness if used excessively	
Functional beverages	Benefits	• Used in malt-based functional drinks, increasing fiber and antioxidant levels	• Acts as a probiotic booster in fermented drinks, improving gut health • Used in sports recovery beverages due to protein and peptide content	• Incorporated into functional teas and antioxidant beverages • Provides anti-inflammatory and anti-microbial properties	101 and 102
	Limitations	• Can contribute to sedimentation issues	• Can cause cloudiness if not properly filtered	• Strong bitterness may limit consumer acceptability	
Antioxidant and bioactive compounds applications in food	Benefits	• Contains polyphenols and dietary fiber, improving oxidative stability • Enhances gut microbiota health and reduces glycemic response	• Rich in β-glucans and peptides, supporting immune function • Modulates inflammatory response and supports cardiovascular health	• Contains flavonoids and terpenes with strong anti-microbial activity • Contributes to immune modulation and oxidative stress reduction	106 and 6
	Limitations	• Can alter food texture if used in high amounts	• Some peptides may interact with other food components, affecting stability	• May introduce a strong, lingering bitterness	

EU Novel Food regulations, are incorporated into protein bars, soups, and cereals for added health benefits.[52,53]

4.2. Bakery and cereal-based products

Incorporating BBPs into bakery and cereal-based products such as bread, cookies, cakes, pasta, and wafers has gained increasing attention due to their high dietary fiber, protein, and bioactive compound content. In wheat bread formulations, SG inclusion at 5–15% significantly increased dietary fiber and essential minerals (magnesium, zinc, phosphorus) while maintaining acceptable volume and texture.[18,76] The fermentation of SG using *L. plantarum* before incorporating it into bread formulations improved dough hydration, increased springiness, enhanced flavor complexity, and increased overall sensory acceptance, making it a viable ingredient for sourdough formulations.[21] In cakes, nutritional enrichment with SG flour improved fiber and protein content but influenced consumer preference. A 40% SG substitution in chocolate cake produced a well-balanced product with a 73.4% sensory acceptance index. However, increasing the substitution to 60% reduced acceptance to 69.7%, likely due to a denser texture and a more pronounced aftertaste. While higher SG levels increased the fiber and protein content, further formulation optimization is still needed to improve sensory appeal.[77] In cookies and wafers, SG improved nutritional content but impacted texture (Fig. 2a and b). An example of SG-enriched wafers is presented in Fig. 2, illustrating their characteristic high porosity and absence of filling.[78] The incorporation of SG into wafer formulations has been shown to enhance textural properties, including increased gumminess, chewiness, springiness, firmness, and cohesiveness, while reducing adhesiveness.[78,79] However, excessive SG addition may negatively affect sensory acceptability and lead to increased hardness, likely due to higher water absorption and the formation of a denser structural matrix. Water activity, an

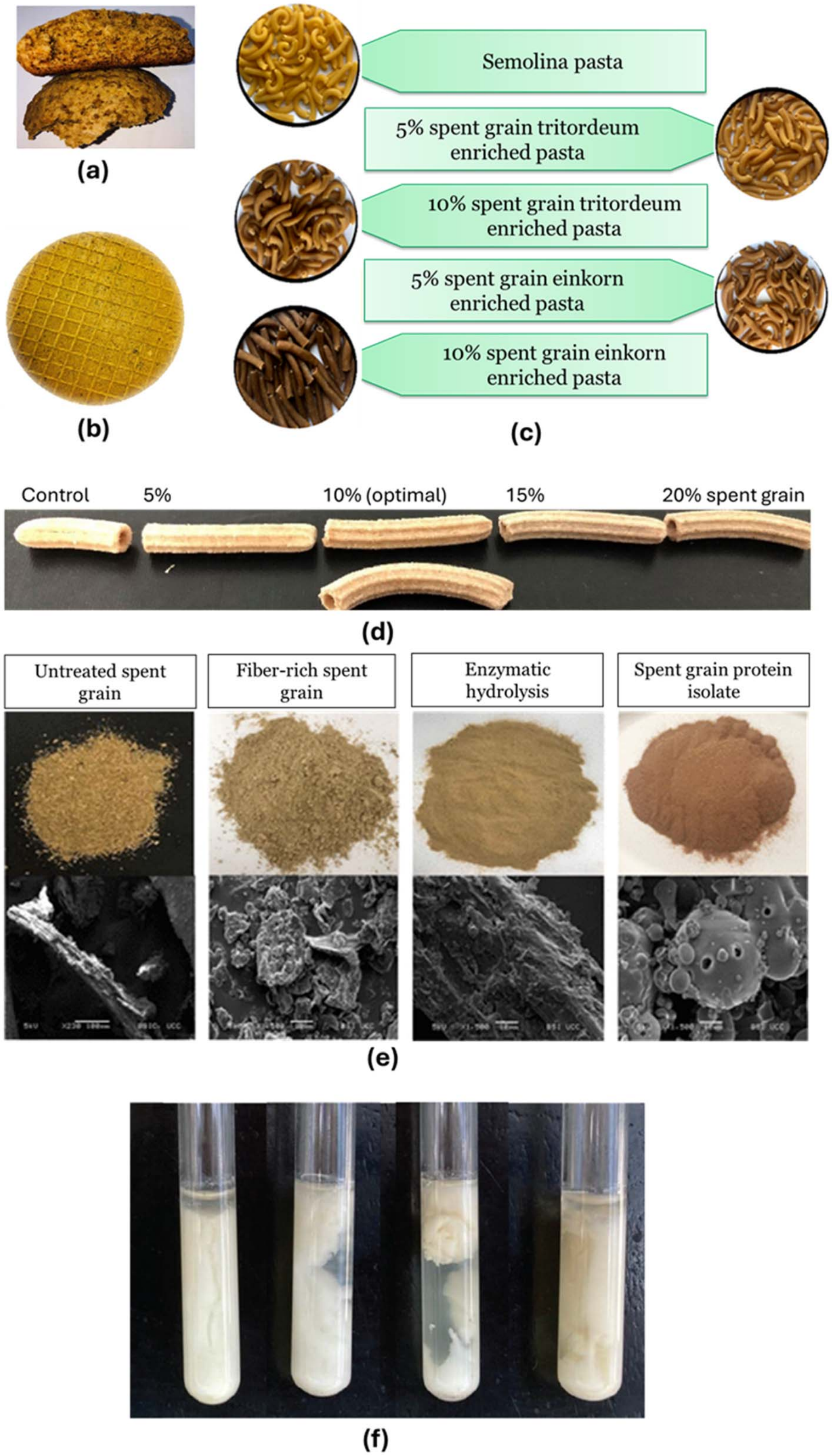

Fig. 2 Brewing BBPs in foods: (a) cookies formulated with SG flour, adapted/reproduced from Chetrariu and Dabija (2023) with permission from MDPI,[78] copyright 2023; (b) wafers containing SG flour, adapted/reproduced from Chetrariu and Dabija (2023) with permission from MDPI,[78] copyright 2023; (c) pasta enriched with 5% and 10% SG flour, showing the shape and consistency of extruded pasta before cooking, adapted/reproduced from Nocente *et al.* (2021) with permission from MDPI,[81] copyright 2021; (d) pasta enriched at 5–20% SG flour, adapted/reproduced from Chetrariu and Dabija (2022) with permission from MDPI,[91] copyright 2022; (e) scanning electron microscope images of untreated and processed SG, displaying structural changes in fiber matrices at a microscopic level, adapted/reproduced from Nyhan *et al.* (2023) with permission from ACS Publications,[85] copyright 2023; and (f) milk-clotting activity of SG extracts, adapted/reproduced from Villegas *et al.* (2024) with permission from MDPI,[84] copyright 2024.

important instrumental indicator of wafer crispiness, should typically fall within the range of 0.39 to 0.52.[79]

SY-derived β-glucan was also applied in bread, enhancing specific volume, crumb lightness, and textural uniformity while increasing fiber content. In contrast, control bread showed reduced volume and darker coloration, likely due to increased Maillard reactions.[80] Moreover, SY fibers showed promise in lowering the glycemic index of baked products, aligning with formulations for diabetic and weight-management diets.[57] In pasta, SG incorporation improved β-glucan content, antioxidant activity, and nutritional value (Fig. 2c).[91] Increasing SG content from 5% to 10% significantly enhanced the protein, total dietary fiber, and β-glucan levels in pasta formulations. Among the variants tested, 10% einkorn SG yielded the highest nutritional enrichment, with a 68% increase in total dietary fiber. In contrast, tritordeum SG, while also improving fiber content (+42%) and β-glucan levels, resulted in higher cooking loss, likely due to a weaker gluten network. Sensory evaluation indicated that pasta enriched with 10% einkorn SG offered the best balance of nutritional improvement and textural quality, whereas tritordeum-enriched pasta exhibited lower acceptability due to increased stickiness and reduced firmness.[81,82] Similarly, the addition of 10% SG in pasta (Fig. 2d) enhanced nutritional value and increased cooking time without negatively affecting texture. However, increasing the level to 15% led to a softer, more brittle texture, elevated cooking loss, and reduced sensory acceptance.[78]

4.3. Fermented dairy products

SG was incorporated into fermented dairy products to enhance nutritional value and support gut health.[83] As shown in Fig. 2e, the native structure of unprocessed SG features a dense lignocellulosic network with intact cell walls. Enzymatic hydrolysis and fermentation treatments disrupt these biopolymer matrices, increasing porosity and surface area. These structural modifications improve digestibility and functional interactions with other ingredients, thereby enhancing emulsification, texture, and mouthfeel in dairy systems.[84,85]

In cheese production, milk-clotting activity of SG extracts, containing proteases derived from various beer types, demonstrated their potential as alternative coagulants. As illustrated in Fig. 2f, variations in clot texture indicated differences in enzymatic profiles among the extracts. Compared to traditional chymosin, some SG-derived enzymes yielded softer or firmer curds, influencing drainage, moisture retention, and final cheese texture. These results position SG extracts as promising substitutes for plant-derived coagulants such as *Cynara cardunculus* and *Ficus carica.*[84]

SY-derived mannoproteins acted as natural emulsifiers and stabilizers, improving texture, water retention, and stability in soft and semi-hard cheeses. These proteins also enhanced meltability and creaminess, making them valuable for low-fat cheese formulation.[6,86] In yogurt, SG-derived β-glucan (0.2–0.8%, w/w) acted as a thickener, reducing fermentation time from 4 to 3 h and forming small spherical aggregates in the matrix. Increasing β-glucan concentration improved textural parameters, including hardness (+19.27%), adhesive force (+21.53%), and adhesiveness (+20.76%), without adversely affecting syneresis, viscosity, or acidity. Sensory analysis revealed the highest acceptability scores (7.2/9) at 0.2% and 0.4% concentrations, while the 0.8% level was less preferred (5/9) due to off-flavors, indicating an optimal addition range for consumer acceptance.[87]

Hot trub has also shown potential as a prebiotic additive in fermented dairy. It supports probiotic viability and improves metabolic activity in yogurt and cheese. Its protein and lipid content contribute to structure and texture, acting as natural binders that enhance mouthfeel and reduce syneresis.[86,88] Moreover, efforts to valorize hot trub as a protein source have focused on optimizing drying methods. Freeze-drying increased protein concentration by up to 65% and preserved superior functional properties compared to hot-air drying, including improved amino acid profiles, higher digestibility (>54%), and enhanced antioxidant and anti-hypertensive activity.[89,90]

4.4. Encapsulating materials for functional food powders

BBPs are increasingly recognized as natural encapsulating materials due to their high content of dietary fiber, protein, and lipids. These properties make them suitable carriers for functional food powders, synbiotics, and antioxidant-rich microcapsules.[92,93] β-Glucans extracted from SY have shown strong potential as natural microencapsulation and cryoprotective agents, effectively protecting probiotic *Lactobacillus* strains during freeze-drying, refrigerated storage, and simulated gastrointestinal digestion, with performance comparable to fructooligosaccharides.[76] Its fibrous matrix also enables controlled release, supporting synbiotic formulations.[94]

A recent study optimized the microencapsulation of *L. plantarum* using SG-derived residues as carriers *via* fluidized bed granulation. The incorporation of 10% indigestible dextrin significantly improved bacterial viability, increasing from 83–87% to 94–95%, at granulation temperatures between 45–65 °C. The resulting powder exhibited low moisture (2–4%) and water activity (0.06–0.22), enhancing storage stability. After 45 days at 25 °C, viable counts remained at 7.3 log colony-forming-unit per g with an 89% survival rate, highlighting SG's efficacy as a prebiotic carrier for probiotic delivery.[95] Similarly, SY-derived β-glucans have been applied as encapsulating agents for probiotics and yeast-derived bioactives (*e.g.*, vitamins and peptides), improving microbial viability during processing and storage, and protecting heat-sensitive compounds.[92,93] Cheese whey (CW) and autolyzed yeast (AY) as encapsulating materials achieved survival rates above 96% post-processing and retained 69–75% viability after 90 days; the CW : AY (50 : 50) formulation showed the best gastrointestinal resistance, with 40–56% survival compared to free cells.[93] SY protein hydrolysates have also been used as natural emulsifiers for sunflower oil microencapsulation, producing stable emulsions (29 mV in zeta potential and 6.6 μm in droplet size) and achieving up to 55% encapsulation efficiency with maltodextrin, alongside enhanced oxidative stability during storage. In addition, SY-derived β-glucans function as protective agents for probiotics and bioactive ingredients, improving microbial survival during freeze drying, storage, and simulated digestion. These findings demonstrate the versatility of SY derivatives as encapsulating and stabilizing agents, enabling the valorization of BBPs in probiotic and bioactive delivery systems.[96]

4.5. Meat alternatives and processed meats

SG and SY have been investigated as partial substitutes for traditional binders and thickeners in processed meats, improving both sensory and nutritional attributes. SG-derived proteins and fiber improved chewiness, texture, and nutrient composition in vegan burgers, sausages, and hybrid meat products. The addition of 5–15% SG in meatballs, sausages, and beef patties was shown to increase dietary fiber and protein while reducing fat content.[57,97] Additionally, the lignin and hemicellulose content in SG improves water retention, contributing to juiciness and tenderness.

A study using 1% SG extract in cooked hams over 12 and 90 days showed increased hardness, chewiness, ash, protein, and free amino acids, with no significant changes in the volatile profile. These changes, unaffected by cooking time, were attributed to stronger gel formation, highlighting the extract's potential as a gel stabilizer in processed meats.[97] Additionally, SY-derived peptides enhanced umami taste, reducing the need for artificial flavor enhancers and supporting their use in plant-based deli meats, sausages, and meat-free nuggets. SY fractions also served as thickeners in processed chicken formulations, improving texture, sensory attributes, and moisture retention.[57,97]

4.6. Functional beverages

BBPs have shown potential in functional beverage development due to their nutritional value and bioactivity. SG was incorporated into protein-rich beverages (3.3% protein), supporting its role as a sustainable nutrient source.[98] Submerged fermentation of a SG-derived beverage with *B. subtilis* WX-17 enhanced its nutritional profile by increasing essential amino acids and reducing carbohydrate content. Antioxidant activity doubled, and total phenolic content increased from 125.7 to 446.74 μg GAE mL^{-1}. *B. subtilis* WX-17 remained viable for six weeks at 4 °C, indicating potential as a probiotic strain.[99] In another application, SG-derived phenolic extracts improved the antioxidant capacity of cranberry juice but showed limited impact on beverages with higher baseline antioxidant levels, such as pomegranate and strawberry smoothies. Antioxidant activity declined post-digestion across all formulations, with no significant differences between enriched and control samples, suggesting matrix-dependent efficacy.[100]

SY has also been explored for functional beverage applications. Its β-glucans were used as probiotic enhancers in fermented and dairy-based drinks, improving probiotic viability and shelf-life.[54,89] Incorporating SY extracts into kombucha, and fermented plant-based beverages improved shelf-life stability and probiotic activity. Beyond fermented drinks, SG and SH-derived polyphenols and terpenes were explored in functional tea blends and antioxidant-enriched beverages.[101,102] SY-derived peptides in these formulations have shown bioactive effects, including cholesterol-lowering and antioxidant properties, while SG polyphenols may help mitigate oxidative stress.

Additionally, BBPs have potential applications in sports recovery drinks and plant-based protein shakes. SG protein hydrolysates offer high digestibility, while SY provides essential amino acids, B-vitamins, and bioactive peptides that aid muscle recovery, reduce inflammation, and support immune function. These formulations could appeal to athletes, fitness enthusiasts, and health-conscious consumers seeking natural protein sources and post-exercise recovery solutions.[103,104]

4.7. Active packaging materials

The valorization of SG into biodegradable packaging materials has gained attraction due to its rich content of cellulose, hemicellulose, lignin, and proteins. These components were utilized to enhance film strength, flexibility, oxygen barrier properties, and anti-microbial stability. The films also exhibited low water vapor permeability, making them competitive with synthetic packaging materials.[105] Nanocomposite films combining SG-derived arabinoxylans and nanofibrillated cellulose exhibited improved mechanical performance, thermal resistance, and UV protection.[106]

Vieira *et al.*,[107] developed cassava starch/polyvinyl alcohol films incorporating SG extract, which enhanced antioxidant activity (263.23 mg GAE per g) while maintaining tensile strength and microstructural integrity. The films also exhibited controlled phenolic release, supporting their application in active food packaging. Similarly, starch-based films with SG provided antioxidant protection (IC50: 2.0 μg mL^{-1} ABTS; 196.05 μg mL^{-1} DPPH) and mechanical stability.[108,109] Biodegradable food trays formulated from BBPs and agricultural residues showed promising properties. Husk-enriched trays exhibited the highest rigidity, while bagasse addition resulted in weaker structures. These trays fully decomposed within 60 days, maintained homogeneity in color and appearance, and demonstrated good malleability as they could be bent without breaking, making them suitable for dry food packaging.[110]

SG and SH-derived phenolics were incorporated into functional coatings and bioactive films to protect perishable foods.[6] Edible coatings derived from these by-products act as barriers against oxygen and moisture, reducing food spoilage and extending shelf-life. When applied to fresh-cut fruits, vegetables, and meat products, these coatings significantly delayed oxidative degradation and microbial growth, providing a natural alternative to synthetic preservatives. Similarly, SH extracts in active food packaging exhibited anti-microbial effects against foodborne pathogens, particularly *L. monocytogenes* and *E. coli.*[106] Brewing polyphenols and terpenes from hot trub further contributed anti-bacterial and anti-fungal properties, enhancing food freshness.

5. Consumer perception and market trends

For newly introduced food products like those upcycled from BBPs, sensory evaluation particularly assessing overall liking

Table 4 Summary of studies on the use of BBPs in various food applications

BBPs (their content)	Food products	Key results	References
SG (10–30%)	Cookies	• Fiber: 1.7–4.8% in SG cookies (*vs.* 1.02% control) • Sensory: All ~7 (liked moderately) • Purchase intent: 78% SG *vs.* 70% control	111
SY	Home-made bread	• β-glucan intake: 65 → 125 mg/serving (meets European Food Safety Authority guideline) • Bread: Darker, springier crumb, increased hexanal compounds • Sensory: no significant differences in overall attributes (trained panel)	112
SG (5–10%)	Macaroni pasta	• Fiber, β-glucan, and antioxidant activity: significantly increased • Sensory: minimal negative effects • 10% SG: best balance of nutrition, technology, and sensory quality	82
SG	Dry pasta	• Nutrition claims: "high protein" (15% protein-rich SG) and "high fibre" (10% fiber-rich SG) • Enriched pasta with SG: excellent technological, nutritional, and sensory quality *vs.* semolina and wholegrain pasta	113
SG (40–60%)	Chocolate cakes	• SG cakes: rich in protein, zinc, fiber • Sensory: 40% substitution most accepted (flavor)	77
SY (β-glucan, 0.2–0.8%)	Skimmed-milk yogurt	• Fermentation time: reduced by 1 h • Sensory: overall liking 5/9, adverse flavor/aftertaste at 0.8% • Potential as yogurt thickener	87
SG	Dairy (cheese coagulant)	• Caseinolytic activity: 60.4–99.6 U per mg, α-casein hydrolysis 78%, κ-casein 56.5% • Milk-clotting activity: comparable to plant-based coagulants • Potentially sustainable cheese coagulant	84
SG (1–3%)	Hamburgers	• Increased fiber by 19.6%, protein by 23.5%, but reduced fat and calories • Improved hardness, gumminess, cooking parameters and antioxidant activity • Sensory: no significant differences *vs.* control • Consumer acceptance: enriched hamburgers well accepted	114
SY (1%)	Cooked hams	• Increased hardness, chewiness, ash, protein, and free amino acids • Volatile profile similar to control • Sensory: no significant changes after 12 and 90 days of storage • Potential gel stabilizer in ham production	97
SG	Protein beverage and bread	• Beverages: >3% protein • Bread: fiber ~3% *vs.* 1.5% in control • Potential for protein- and fiber-enriched beverages and bakery products	98
SY	Microencapsulation of sunflower oil	• Encapsulation efficiency: 55% (+87% *vs.* without maltodextrin) • Powder stability: oxidation resistant 4 weeks at 45 °C	92
SY	Protective agent for probiotic lactobacilli during freeze drying & storage	• Probiotic survival: β-glucan maintained viability during freeze drying, 90–120 days of storage, and simulated gastrointestinal digestion • Protective ability: similar to fructooligosaccharides	76
SY	Oral carriers for bioactives (food/biomedical)	• Microcapsules resisted digestion: 44–63% digested • Digested material recognized by immune lectins • Spherical shape preserved, recognized by Dectin-1 receptor • Potential as immunomodulatory oral carriers	22
SG	Vegan probiotic powdered product	• Probiotic survival: *L. plantarum* NKUST 817 increased from 82.6–87.0% to 93.5–95.2% • Good powder flowability • Stability: 45 days, viable count 7.29 log colony-forming-unit per g, survival 88.7%	95

Table 4 (*Contd.*)

BBPs (their content)	Food products	Key results	References
SG extract	Starch-based active biopolymer films	• Antioxidant activity: ABTS IC_{50} = 2.0 μg mL^{-1}, DPPH IC_{50} = 196 μg mL^{-1} • Phenolic release: 163–166 mg GAE mL^{-1} over 4 h (controlled) • Film properties: rough but intact surface, good stability, mechanical strength unchanged	108
SG extract	Biodegradable active food packaging	• Antioxidant activity: ABTS IC_{50} = 186 μg mL^{-1}, DPPH > 250 μg mL^{-1}, TPC = 263 mg GAE per g extract • Mechanical properties: films thicker/denser, tensile strength, and elongation unaffected • Sustained phenolic release, promising for shelf-life extension	23
SG arabinoxylans	Nanocomposite films for food packaging	• Thermal/mechanical: stable up to 230 °C, modulus up to 7.5 GPa • Bioactivity: 90% DPPH antioxidant activity, anti-bacterial (*S. aureus*, *E. coli*), and anti-fungal (*C. albicans*) effects • Potential as bioactive packaging system	106

provides essential insights into consumer acceptance, as the sensory attributes such as taste, texture, and appearance are often key factors influencing purchase intention. Since these products involve unconventional ingredients, understanding consumer preferences through sensory testing is critical for the product development and market success.[115] The main purposes of valorizing BBPs for foods are to create a sustainable, nutritious, and economically viable food system.[3,5] In most applications of BBPs in foods, they are utilized either as ingredients in food formulations or through the extraction of their functional compounds, which are subsequently fortified into foods, both approaches aiming to enhance the nutritional value and functionality of the final products. However, due to their intrinsic properties, such as the bitterness and astringency of SH[29] and the high insoluble dietary fiber content in SG,[7] their incorporation into foods significantly affects sensory attributes such as appearance, texture, and flavor. Consequently, the amounts used in foods must align with consumer acceptance,

Table 5 Reported studies evaluated the sensory acceptability levels of food products containing BBPs

BBPs (added level)*	Food products	Sensory acceptance level (%)	References
SG (5 &10%)	Bread, pizza & breadsticks	5	127
SG (5, 10, 15 & 20%)	Bread	10	128
SG (5, 10 & 20%)	Bread	10	129
SG (20%)	Bread	20	130
SG (30%)	Shortbread	30	131
SG (10, 15 & 25%)	Snacks (crispy-slices)	10	132
Fresh SG (15, 25 & 50%)	Cookies	25	79
SG protein isolates (2, 4, 6%)	Muffin	2	133
SG (20 & 30%)	Muffin	30	134
SG (10, 15 & 20%)	Muffin	15	135
Sterilized & fermented SG (15, 30%)	Biscuit	30	136
SG (40 & 50%)	Biscuit	40	137
SG (20%)	Biscuit	Acceptable	138
SG (5, 10 & 20%)	Dry pasta	5	82
SG (0.35, 2.8 & 8.3%)	Pasta	2.8	117
SG (barley, barley & wheat, barley & rice, barley & maize; 5, 10, 15 & 20%)	Noodle	10 (especially barley + maize)	139
SG (3 & 5%)	Hybrid sausage	3	140
SY (1.96%)	Bread	1.96	112
SY extract (1%)	Cooked ham	1	97
SY β-glucan powder (0.2, 0.4, 0.6 & 0.8%)	Skimmed yogurt	0.8	87
SY mannoprotein (0.8%) & SY mannoprotein (0.4%) & soy lecithin (0.4%)	French salad dressing	0.8	141
SH (debited & dried; 5, 10 & 15%)	Fresh pasta	10	89
SH (debited & dried; 7.34%)	Ice cream	Low acceptancy	88
SH (debited & dried)	Processed cheese	≤1%	86

which can be determined through sensory evaluation. Table 5 summarizes research studies that investigate the levels of BBPs incorporated into various food products at which sensory attributes are considered acceptable by consumers. It is evident from the table that the levels of BBPs are relatively low and vary across different food products, even among similar products in different studies. Solid foods (*e.g.*, bread and pasta) are more suitable for incorporating BBPs, as their physical state and texture are less affected by BBP addition compared to liquid products (*e.g.*, chocolate milk).[116] Variations in the particle size of BBP powders are another factor influencing the sensory characteristics of fortified products. This may explain the differences in the recommended levels for similar products across various studies. Large and coarse particles (>200 μm) can contribute to a less smooth and uniform texture, resulting in a gritty or unpleasant mouthfeel in pasta.[9,117] Conversely, extremely fine particles (90 μm) of SG may not be ideal for pasta preparation, as they can disrupt rheological properties.[113] Similarly, for muffins supplemented with SG, the sensory acceptability level for SG with a particle size of 212–850 μm was 15%, while that for SG with a particle size of < 212 μm was 5%.[118] These findings highlight the importance of optimizing particle size to achieve desirable sensory and functional properties in BBPs-fortified products.

However, sensory evaluation is only one of many factors determining consumer acceptance to upcycled food products. The key determinants can be classified as individual factors (*e.g.*, environmental awareness, demographics, price sensitivity, and psychological drivers); contextual factors (*e.g.*, communication strategies, trust, and transparency); and product-related factors (*e.g.*, product category, safety concerns, and hedonic factors). These factors are interconnected and overlapped, for example the personal factors can be influenced by the context, or determine how a product is perceived.[119] Targeted communication strategies, such as rational messaging that highlights practical benefits and factual information, have been shown to increase consumers' willingness to pay for upcycled food products.[120] These insights are supported by studies on product labelling and consumer preferences. Curutchet *et al.*,[121] found that consumer purchase intentions for SG-based fiber-enriched burgers were primarily driven by the product brand rather than fiber enrichment details on the label. Brand loyalty and limited time for decision-making often result in consumers overlooking detailed label information. However, specifying the fiber origin with appropriate terms (*e.g.*, "with barley fiber" instead of "by-product", "circular economy", or "reducing waste") and incorporating sustainability logos significantly increased consumer interest. Similarly, Varghese *et al.*,[122] reported that including information about SG enhancement and sustainability logos on product labels increased consumers' willingness to pay for SG-fortified bread and chocolate desserts. However, the most important attribute influencing purchase intention differed between bread and chocolate desserts: product brand for bread and price for chocolate dessert. Additionally, consumer acceptance of SG-enriched products is strongly influenced by the presentation of product information. Curutchet and colleagues,[116] found that clear description of SG benefits and sustainability logos on labels significantly increased purchase intentions across SG-fortified bread, pasta, and chocolate milk. Eye-tracking experiments revealed that claims regarding the fiber source, such as "malted barley" rather than "by-product" consistently attracted more attention, positively correlating with perceptions of healthiness and purchase intention. The relationship between sensory perception and consumer expectation further depends on the product type. For staple foods such as bread (8.3% SG addition) and pasta (2.8% SG addition), consumers were willing to accept trade-offs in texture and flavor for the health benefits of added fiber. In contrast, indulgent products such as chocolate milk (0.35% SG addition), where smooth texture and rich flavor are expected, were unaccepted due to gritty texture and off-flavors caused by SG. Also, unlike semi-solid foods such as bread and pasta, liquid products like chocolate milk are more sensitive to textural changes from SG addition, further influencing consumer acceptance.[117]

Combest and Warren,[123] employed focus group discussions with 37 college students to examine consumer acceptance of SG-fortified foods. They found that experienced whole grain consumers, accustomed to coarser textures and earthy flavours, were more receptive to SG-fortified foods compared to refined grain consumers, who preferred smoother textures and milder tastes. This suggests whole grain consumers could be a key target market for SG-fortified products. The study also emphasized the need for consumer education to raise awareness of health benefits and improve acceptance. Similarly, Naibaho *et al.*,[124] conducted an online survey of 122 participants worldwide to evaluate consumer knowledge, opinions, and willingness to purchase SG-fortified foods (bread, cookies, pasta, yogurt, and ice cream). Before education, 57.4% of participants were unaware of SG, but after watching an educational video, 76.2% expressed willingness to purchase SG-fortified foods for their health and sustainability benefits. Familiar products like bread, pasta, and cookies were most preferred, while yogurt and ice cream received lower acceptance due to sensory concerns such as texture. This finding agrees with that previously reported.[116,117] Key barriers identified included taste, texture, price, and perceptions of SG as waste, along with concerns about food safety, regulations, and allergens. Crofton and Scannell,[125] also highlight the importance of a consumer-led approach in developing SG-based snacks. By involving consumers early in the process, they identified key drivers of preference, such as the health and convenience appeal of crispy crackers, while addressing challenges like textural issues in twisted breadsticks. Together, these studies underline that sensory attributes, familiarity, and education are critical for improving consumer acceptance of SG-fortified foods.

The global market size of upcycled foods was valued at 54.5 billion USD in 2022 and is expected to grow at an annual growth rate (CAGR) of 5.7% from 2023 to 2032. Based on the sources of by-products, the food brewing and distillery by-product segment accounted for almost one-third of the upcycled food products market share in 2022.[126] Many food products produced from BBPs, especially SG are commercially available (Table 6). However, the number of available products and their market share are still far from reaching their full potential, considering

Table 6 Commercial food products containing BBPs

BBPs	Key food products	Companies	Sources
SG	Crackers, chips & cookies	Brewer's Foods	https://www.brewersfoods.com/
SG, SY	Marmite, soups, sauces & bread	Unilever	https://www.marmite.co.uk/
SG, SY	Vegemite, crackers & biscuits	Bega Cheese Limited	https://www.vegemite.com.au/
SG	Protein powders (EverPro)	EverGrain	https://www.evergrainingredients.com/
SG	Crisps, crackers & flours	Agrain	https://www.agrainproducts.com/
SG	Bakery, snacks, sweet, pasta, noodles & beverages	Upcycled Foods (ReGrained)	https://www.upcycledfoods.com/
SG, SY	Chips & snacks	Planetarians	https://www.planetarians.com/
SG	Flours, protein isolates & soluble dietary fibers	Grainstone	https://www.grainstone.com.au/
SG, SY	Muesli, pizzas, potato chips & meat alternatives	Brewbee	https://www.brewbee.ch/
SY	Nutrient-rich proteins & dietary fibers	Yeastup	https://www.yeastup.com/
SG	Sourdough bread	Spent Goods	https://www.spentgoods.ca
SG	Functional protein & fiber ingredients	Circular Food Solutions	https://www.circular-food-solutions.com/
SG	Flours	Backcountry Mills	Not available
SG	Low-carb, high-protein flour, pancake & waffle mix	Grain4grain	Not available
SG	Baking mixes & ready-to-eat baked goods	Susgrainable	https://www.susgrainable.com/
SG	Flour, baking mixes & protein powders	GroundUp Eco-ventures	https://www.groundupev.com/
SG	Crisps	Rutherford & Meyer	https://www.rutherfordandmeyer.com/
SG	Flour, cookies, brownies, bread, chapatis, pizzas & laddus	Saving Grains	https://www.savinggrains.in/
SG	Baking mixes & snacks	CoRise	https://www.corise.ca/
SG	Cracker & chips	ReBon	https://www.rebon-quebec.com/

the abundance of products and food applications which have been investigated in the field. As demand for sustainable, waste-reducing, and nutritious solutions grows, opportunities for brewing BBP-derived food products are expanding. However, companies must focus on product innovation, consumer education, supply chain partnerships, and eco-friendly certifications to promote these products.[85]

6. Challenges and future work in valorization of brewing by-products

The valorization of BBPs offers a promising pathway to enhance sustainability and promote resource efficiency within the agri-food sector. Despite their nutritional richness and functional potential, the large-scale integration of BBPs into food systems faces several practical and systemic challenges. These include inconsistencies in raw material availability, high perishability, limited consumer acceptance, regulatory ambiguity, and intense market competition. Overcoming these barriers requires coordinated efforts across the supply chain, along with targeted research and innovation. This section outlines the key challenges hindering the widespread application of BBPs and presents strategic considerations to support their effective utilization in food and related industries.

One major challenge is ensuring a stable and consistent supply of BBPs. Variability in composition, quality, and quantity across different breweries, coupled with increasing demand, complicates reliable sourcing. Establishing collaborations with multiple breweries and developing regional supply networks can mitigate these issues. Such strategies reduce dependence on single suppliers, enhance logistical efficiency, and promote consistency in product quality and formulation.

The perishable nature of BBPs poses an additional obstacle, as rapid degradation can occur without proper preservation and handling. To address this, preservation methods such as drying and freezing are recommended to extend shelf life. Furthermore, implementing efficient logistics including expedited transportation, cold-chain storage, and rapid processing can help maintain the functional integrity and safety of BBPs.

Consumer acceptance is another critical barrier. Although BBPs offer recognized nutritional and environmental benefits, skepticism regarding their taste, safety, and quality persists. Addressing this issue requires targeted consumer education initiatives that communicate the value of upcycled ingredients. Collaborations with trusted influencers or sustainability certification organizations may further enhance consumer confidence by associating BBP-based products with credible and environmentally responsible values.

Regulatory uncertainty also remains a significant concern in the evolving upcycled food sector. Existing legislation regarding the use of BBPs in food applications is often ambiguous or subject to change. Continuous monitoring of relevant food safety standards and proactive engagement with regulatory authorities are essential to ensure compliance and facilitate product approval.

Finally, companies must navigate competition from both conventional food products and other sustainable alternatives. Effective market differentiation can be achieved by highlighting the unique nutritional and environmental attributes of BBP-derived products. Strategic investments in branding and third-party eco-certifications can further strengthen product visibility and credibility among environmentally conscious consumers.

7. Conclusion

The effective valorization of BBPs holds significant promise for enhancing food system sustainability and minimizing waste. SG, SY and SH are rich in proteins, dietary fibers, polyphenols, and bioactive compounds, making them valuable ingredients for novel food formulations. Advanced extraction techniques, such as subcritical water extraction, enzymatic hydrolysis, and microbial fermentation, have shown significant potential in improving the bioavailability and functionality of these BBPs. Their applications extend beyond conventional food ingredients to include functional food powders, meat alternatives, and active food packaging. However, the incorporation of BBPs into foods must overcome challenges related to sensory attributes, stability, and large-scale processing to ensure commercial viability.

Consumer acceptance remains a key factor in the successful market integration of upcycled BBPs. While sustainability awareness is increasing, concerns about taste, texture, and safety still affect purchasing decisions. Effective communication strategies, such as transparent labeling and sustainability claims, can enhance consumer trust and willingness to accept these products. Additionally, collaborations between the food industry, researchers, and policymakers are essential for optimizing processing techniques and developing regulatory frameworks that support the utilization of BBPs in food applications. The utilization of BBPs offers opportunities to reduce food waste and support a circular economy. With growing consumer demand for eco-friendly products and plant-based foods, BBPs, especially SG, are valuable for transforming into food products and other applications, such as biodegradable packaging. However, for BBPs-containing foods to be widely accepted, strategies focused on product innovation, consumer education, and regulatory compliance must be addressed.

Author contributions statement

Abedalghani Halahlah: conceptualization, visualization, writing – original draft preparation, writing – review & editing; Kellil Abdessamie: conceptualization, writing – original draft preparation; Susanna Peltonen: supervision, funding acquisition, writing – review & editing, Thao M. Ho: conceptualization, methodology, supervision, formal analysis, writing – original draft, writing – review & editing.

Conflicts of interest

The authors report there are no competing interests to declare. The authors used ChatGPT for language improvement.

Data availability

No primary research results, software or code have been included, and no new data were generated or analysed as part of this review.

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